The Radial Acceleration Relation of Galaxies

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In collaboration with:

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Marcel Pawlowski (University of California - Irvine)

Outline:

1. The SPARC Galaxy Database

2. Results for Late-Type Galaxies (S & dIrr)

3. Results for Early-Type Galaxies (E, S0, dSph)

SPARC

Spitzer Photometry & Accurate Rotation Curves

Database for 175 late-type galaxies (S & dIrr):

www.astroweb.cwru.edu/SPARC

Lelli, McGaugh, Schombert 2016, AJ

SPARC
Spitzer Photometry & Accurate Rotation Curves

- HI Rotation Curves for 175 galaxies

- 30 years of HI obs with WSRT, VLA, ATCA.
- PhD theses from the University of Groningen
  Begeman 1987; Broeils 1992; Verheijen 1997; de Blok 1997; Swaters 1999; Noordermeer 2005; Lelli 2013 + other studies
- Hybrid Hα/HI rotation curves for ~30% sample
  McGaugh+2001; Kuzio de Naray+2006, 2008 + other studies.

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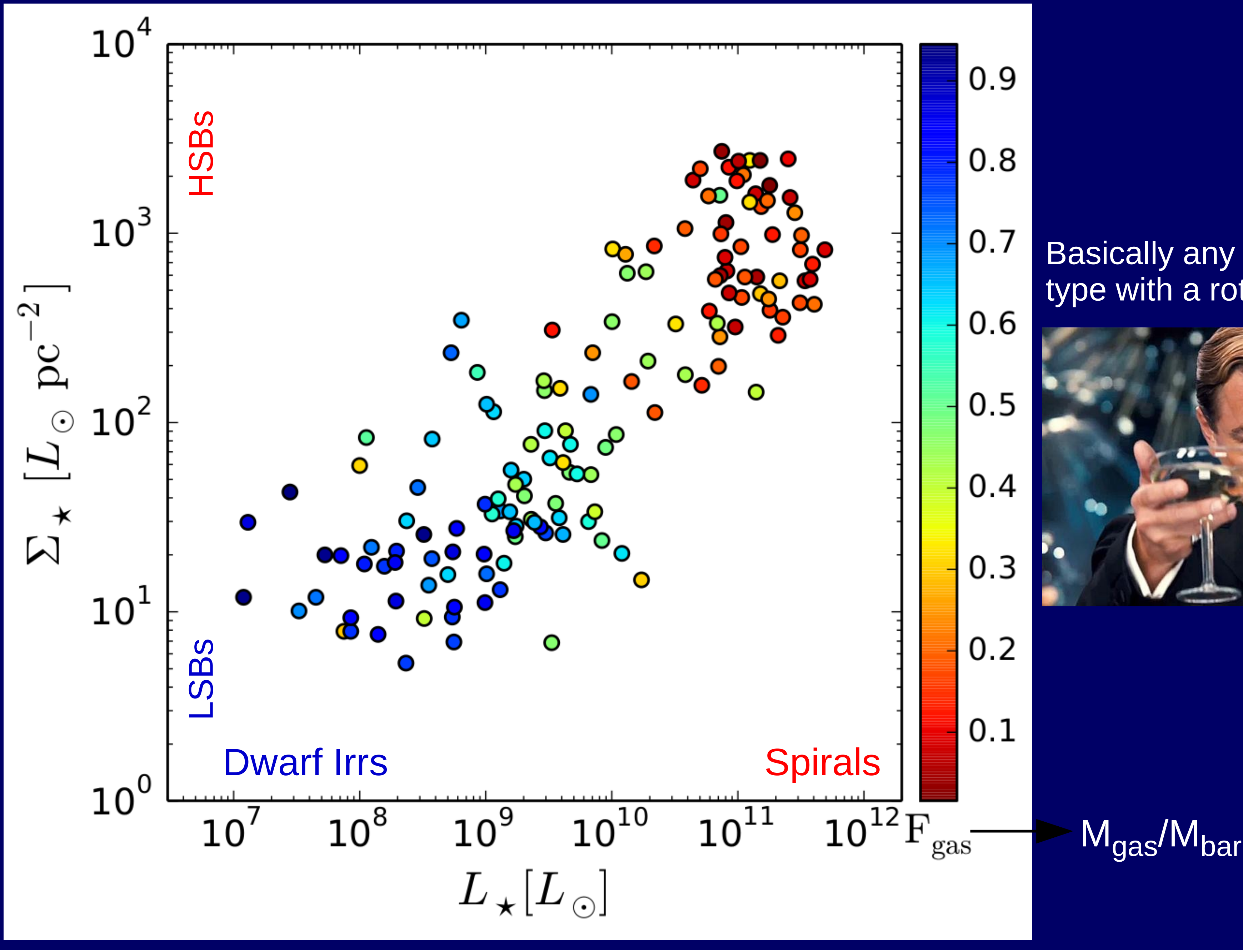
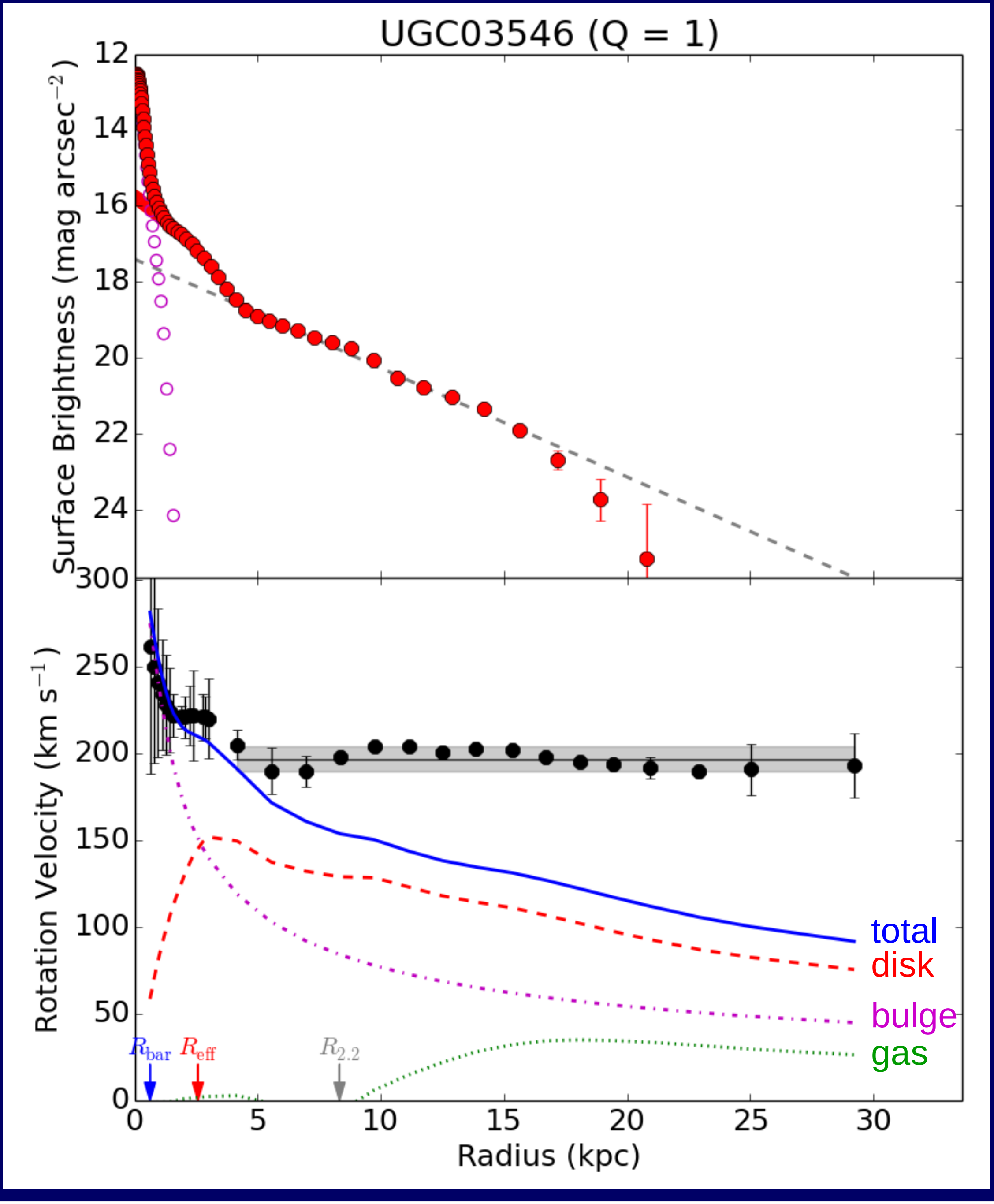
- **Homogeneous Photometry at 3.6 μm**
  - Optimal tracer of the stellar mass: $M_* = \Upsilon_* L$
  - Smaller variations of Υ_* in the NIR than optical
    Bell & de Jong 2001; Martinsson+2013; Meidt+2012, 2014; McGaugh & Schombert 2014; Schombert & McGaugh 2014; Querejeta+2015; Röck+2015; Herrmann+2016; Norris+2016.

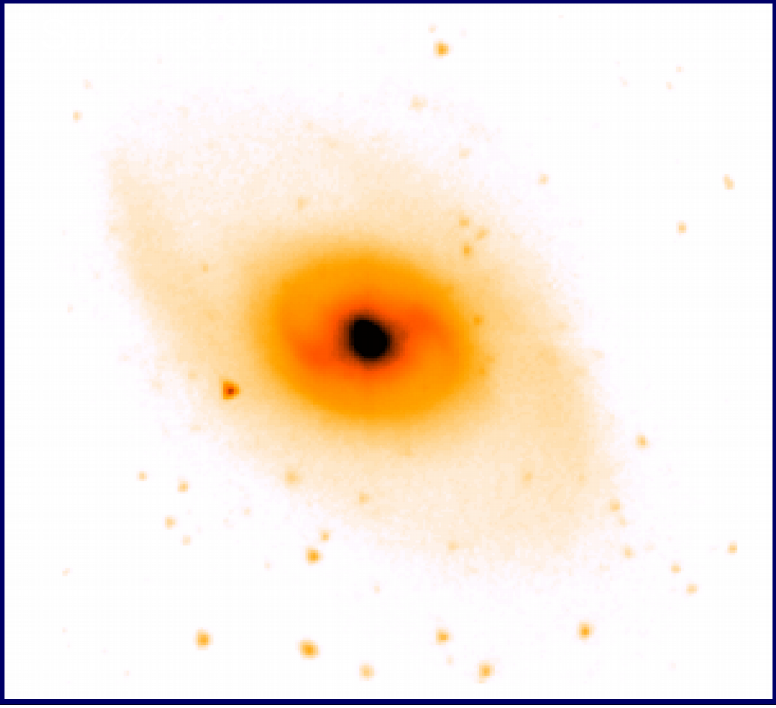
Widest possible range of disk properties



Basically any known galaxy type with a rotating HI disk!

Example: High-Mass HSB Spiral

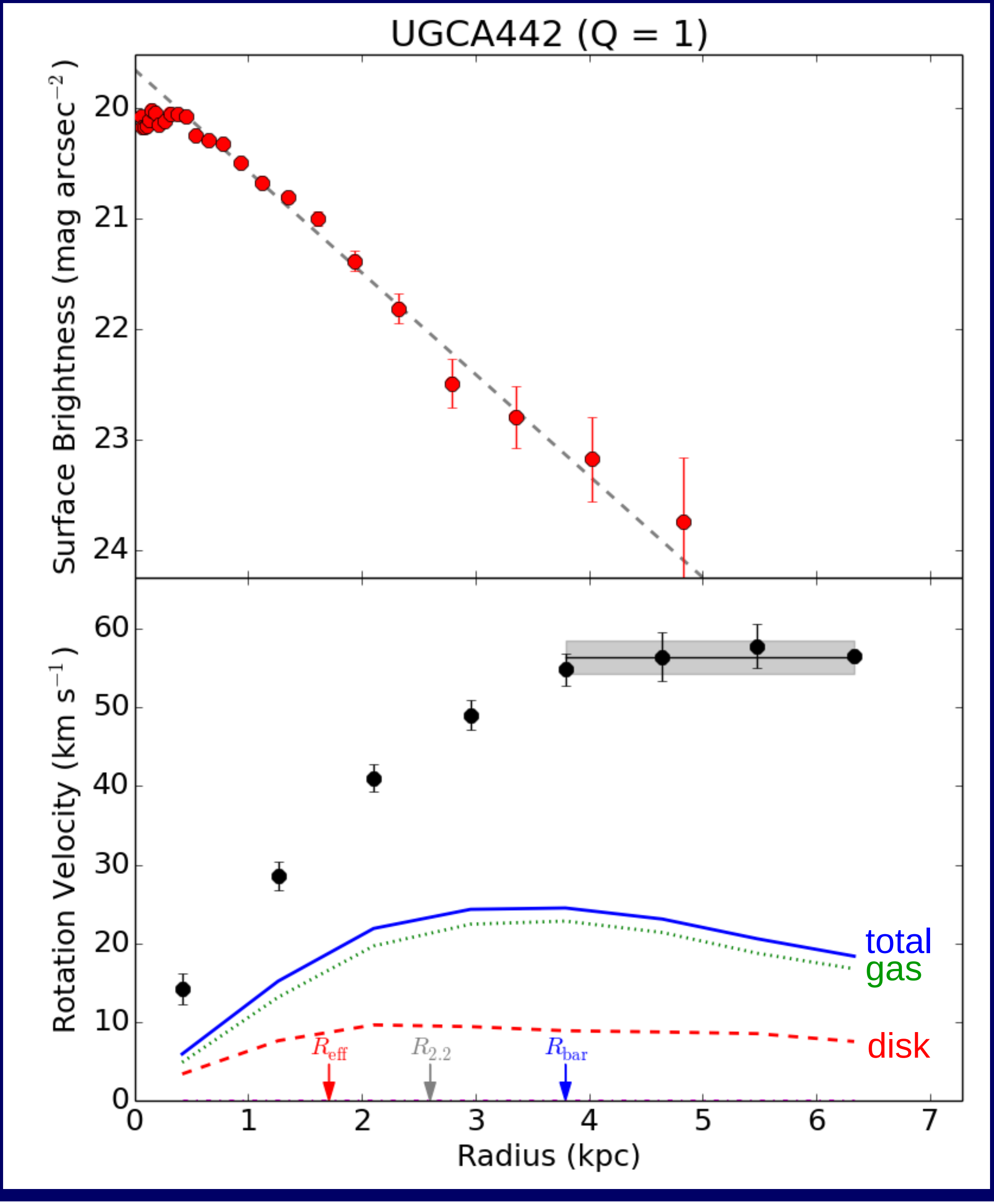


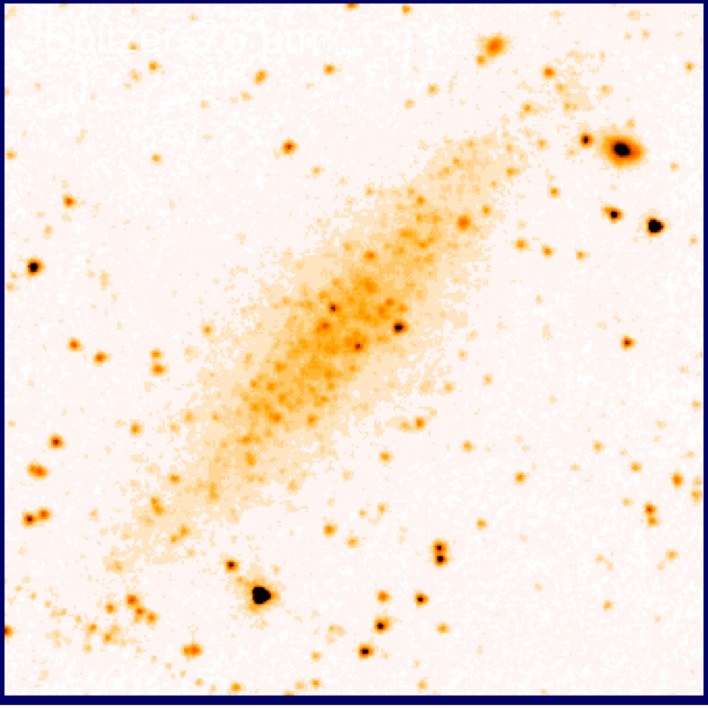


$$\nabla^2 \Phi_{bar}(R,z) = 4\pi G\ \rho_{bar}(R,z)$$

- Vertical Structure:
  - Disks: $\exp(-z/h_z)$ with $h_z \propto h_R$
  - Bulges: spherical symmetry
- Stellar mass-to-light ratio:
  - $\Upsilon_* = 0.5\ M_\odot/L_\odot$ for disks
  - $\Upsilon_* = 0.7\ M_\odot/L_\odot$ for bulges

Example: Low-Mass LSB Dwarf





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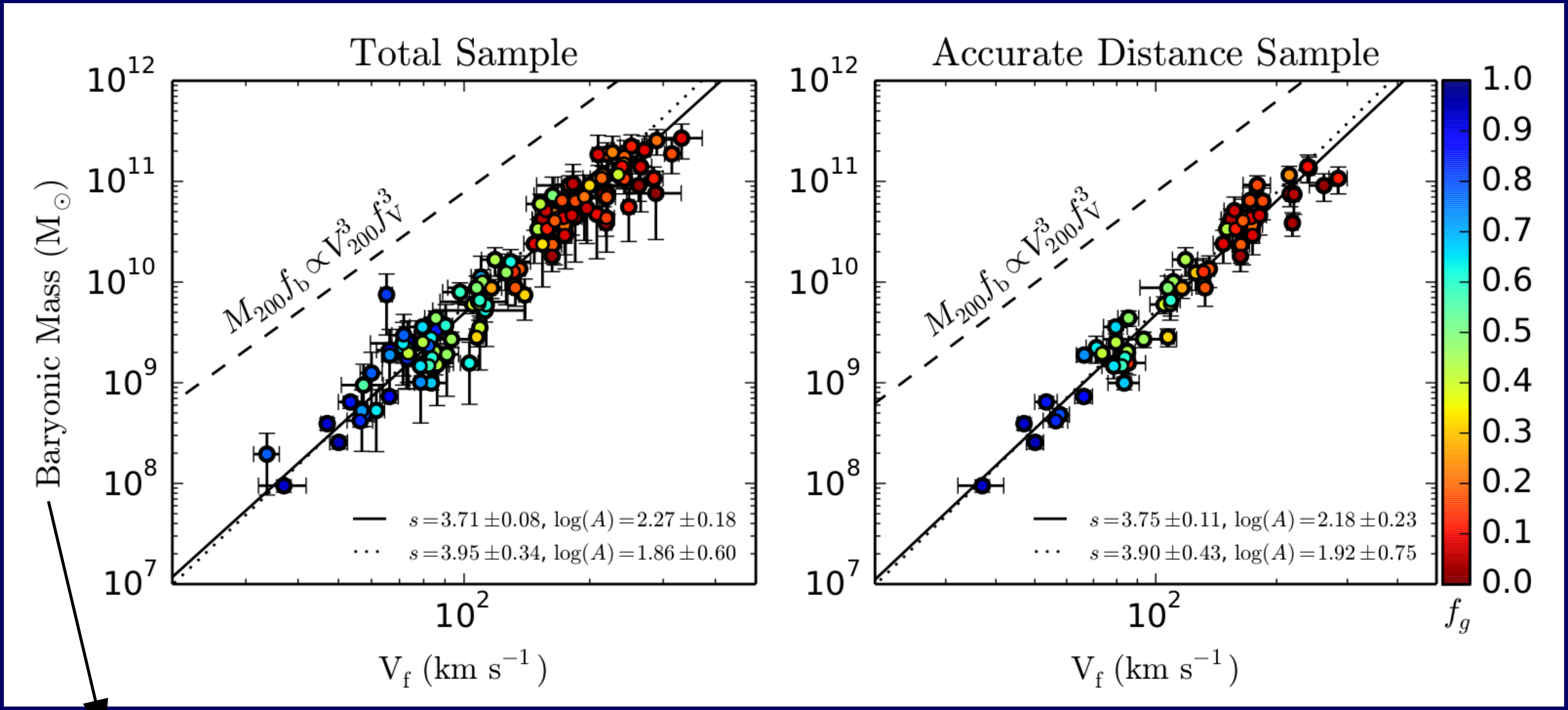
Baryonic Tully-Fisher Relation (BTFR)



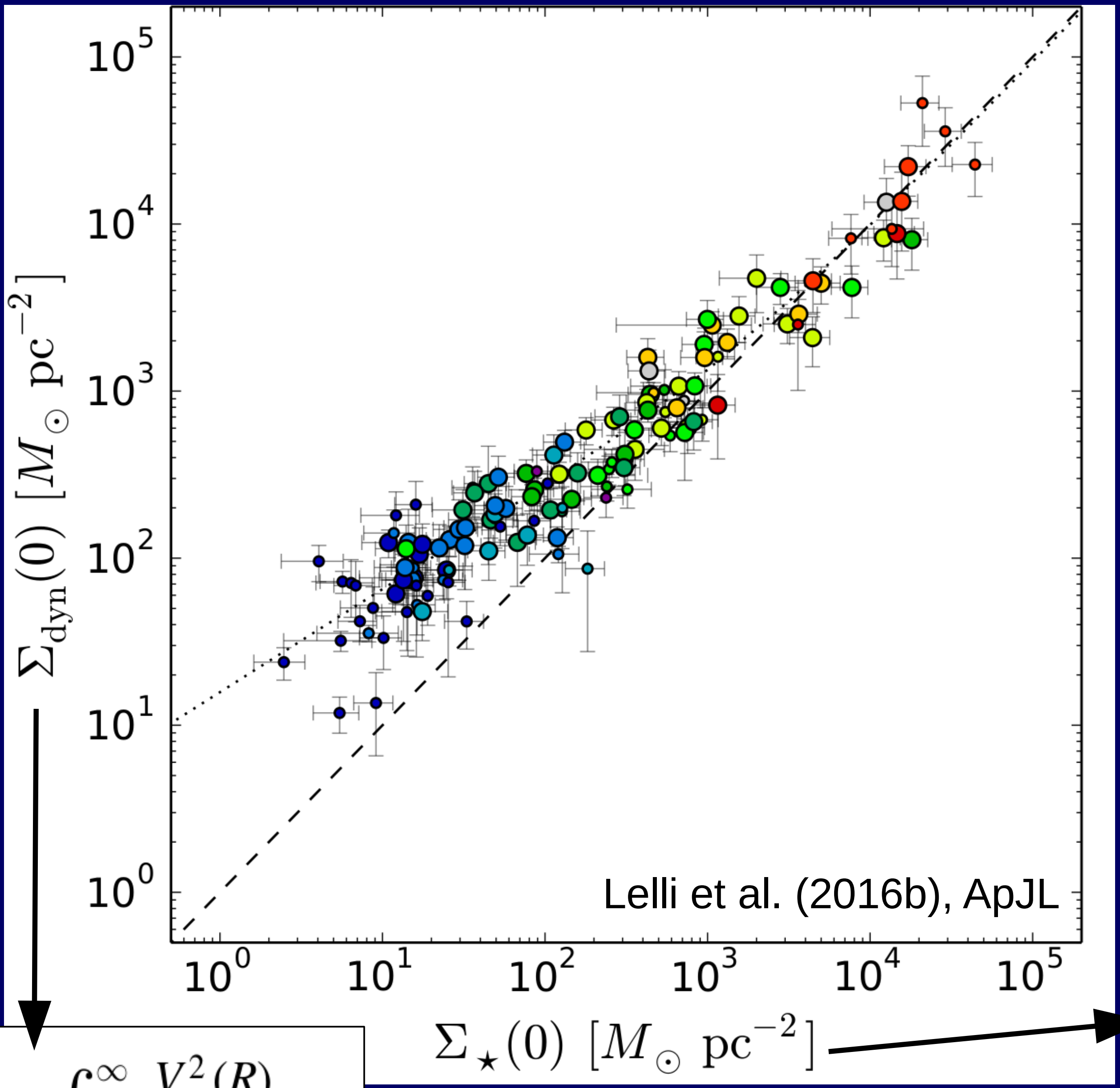
$M_* + M_{gas} \propto D^2$

Lelli, McGaugh, Schombert (2016a), ApJL

GOLDEN RULE: As the data quality increases, the BTFR scatter decreases!

Upper limit on the intrinsic scatter: <0.11 dex (~25%)

Central Density Relation (for R → 0)



For all galaxies:

$\Upsilon_{\rm disk} = 0.5\ M_\odot/L_\odot$

$\Upsilon_{\rm bulge} = 0.7\ M_\odot/L_\odot$

Central Stellar Surface Density

$$\Sigma_{\rm dyn}(0) = \frac{1}{2\pi G}\int_0^\infty \frac{V^2(R)}{R^2}dR,$$

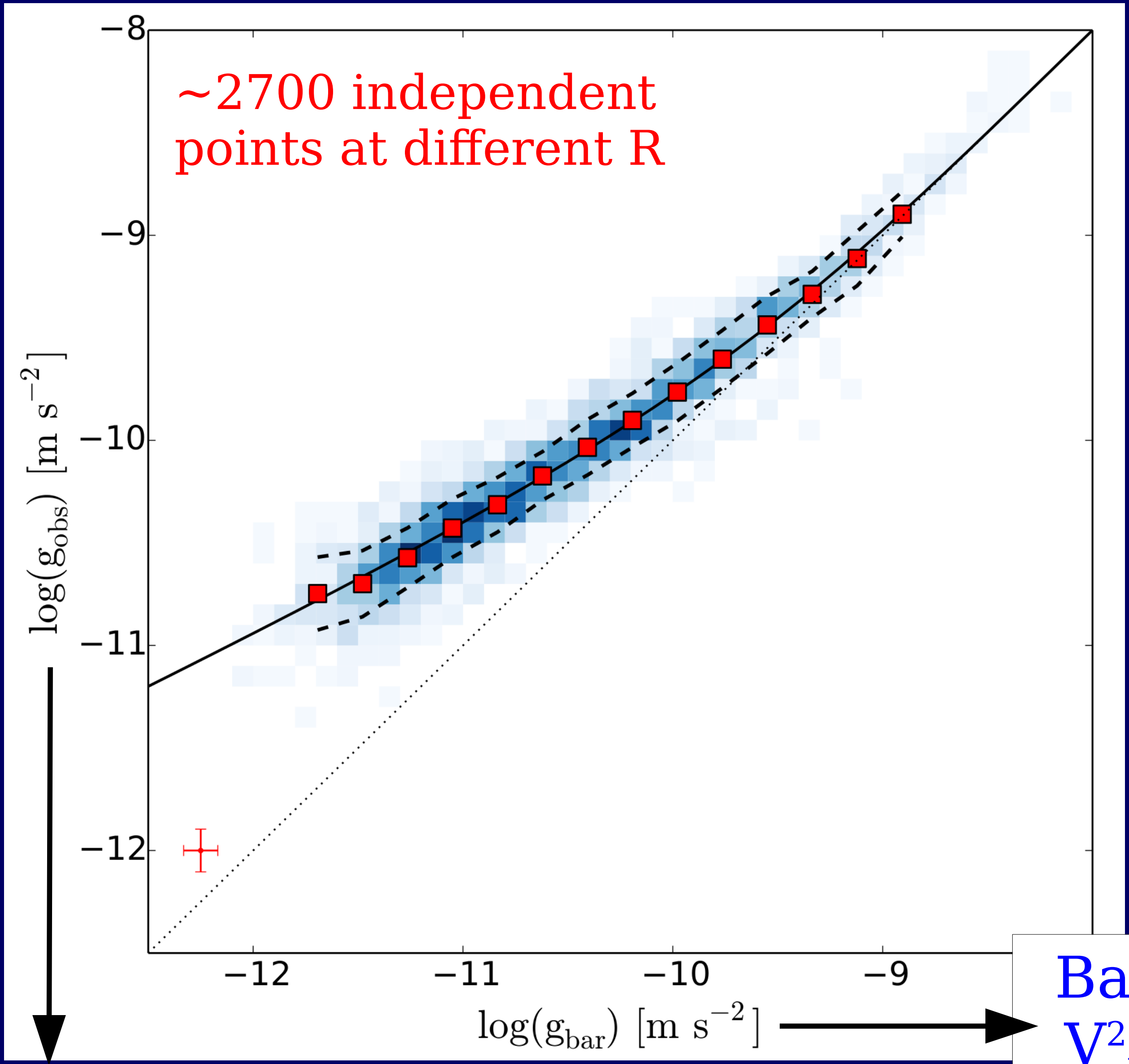
Toomre (1963): Central Dynamical Density for a Self-Gravitating Disk.

2. Radial Acceleration Relation of Late-Type Galaxies

McGaugh, Lelli, Schombert 2016, PRL

Lelli, McGaugh, Schombert, Pawlowski 2017, ApJ

<u>Local</u> link between baryons and DM



For all galaxies:

$\Upsilon_{disk} = 0.5\ M_\odot/L_\odot$

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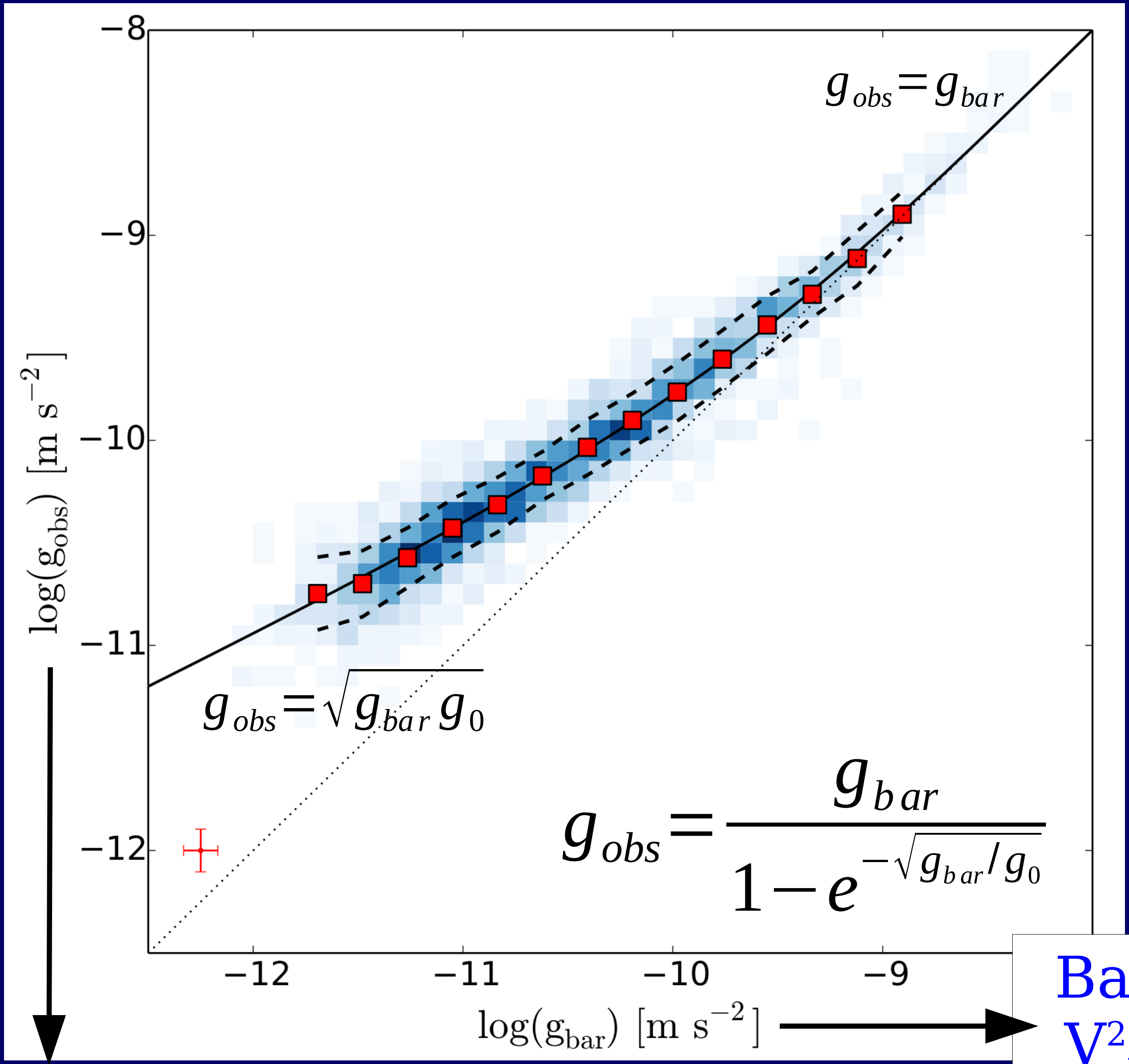
Total Acceleration: $V^2_{obs}/R = -\nabla\Phi_{tot}$

Baryonic Force:

$V^2_{bar}/R = -\nabla\Phi_{bar}$

$\nabla^2\Phi_{bar} = 4\pi G\ \rho_{bar}$

Local link between baryons and DM



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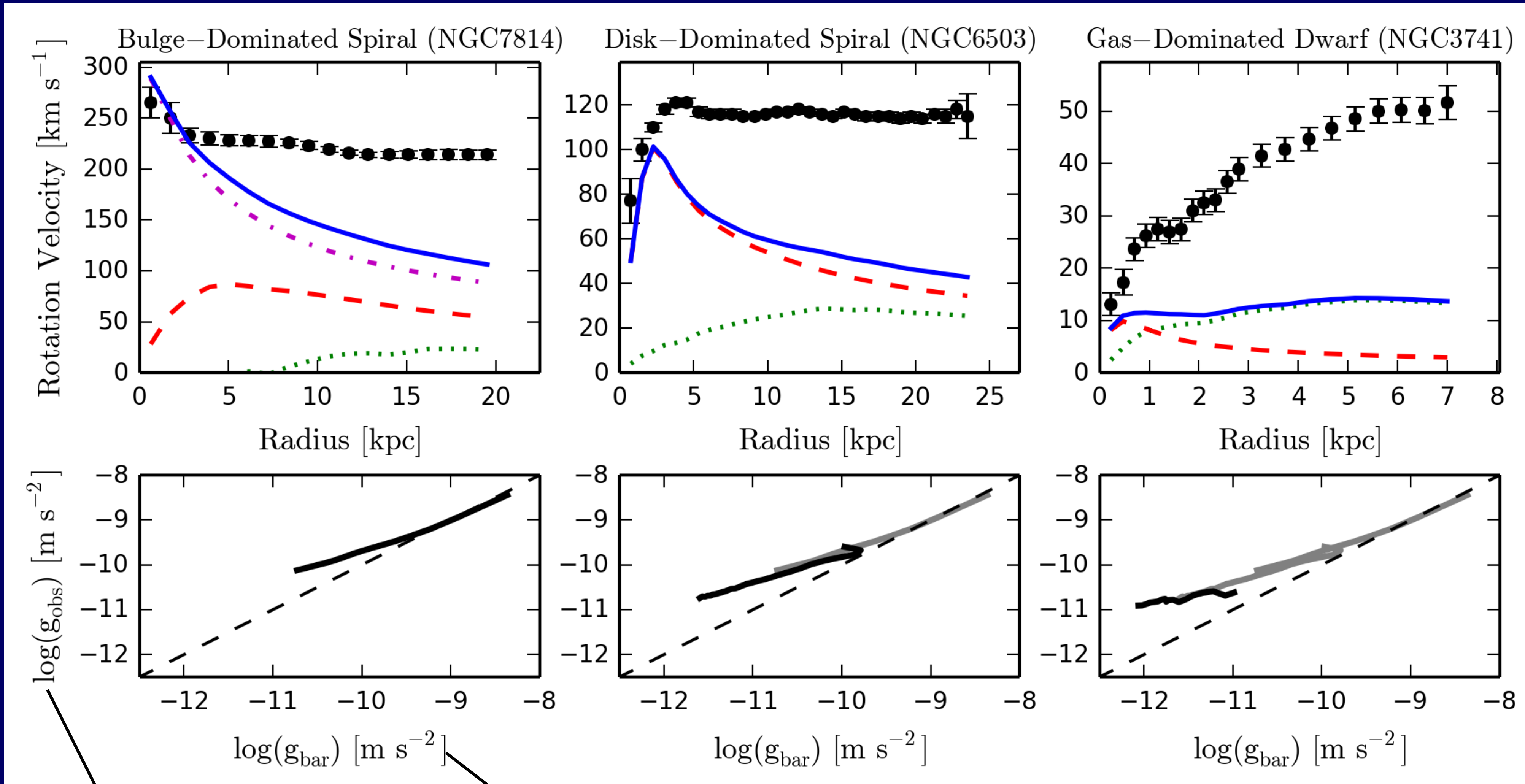
Very different galaxies but ONE relation



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$V^2_{bar}/R = -\nabla\Phi_{bar}$

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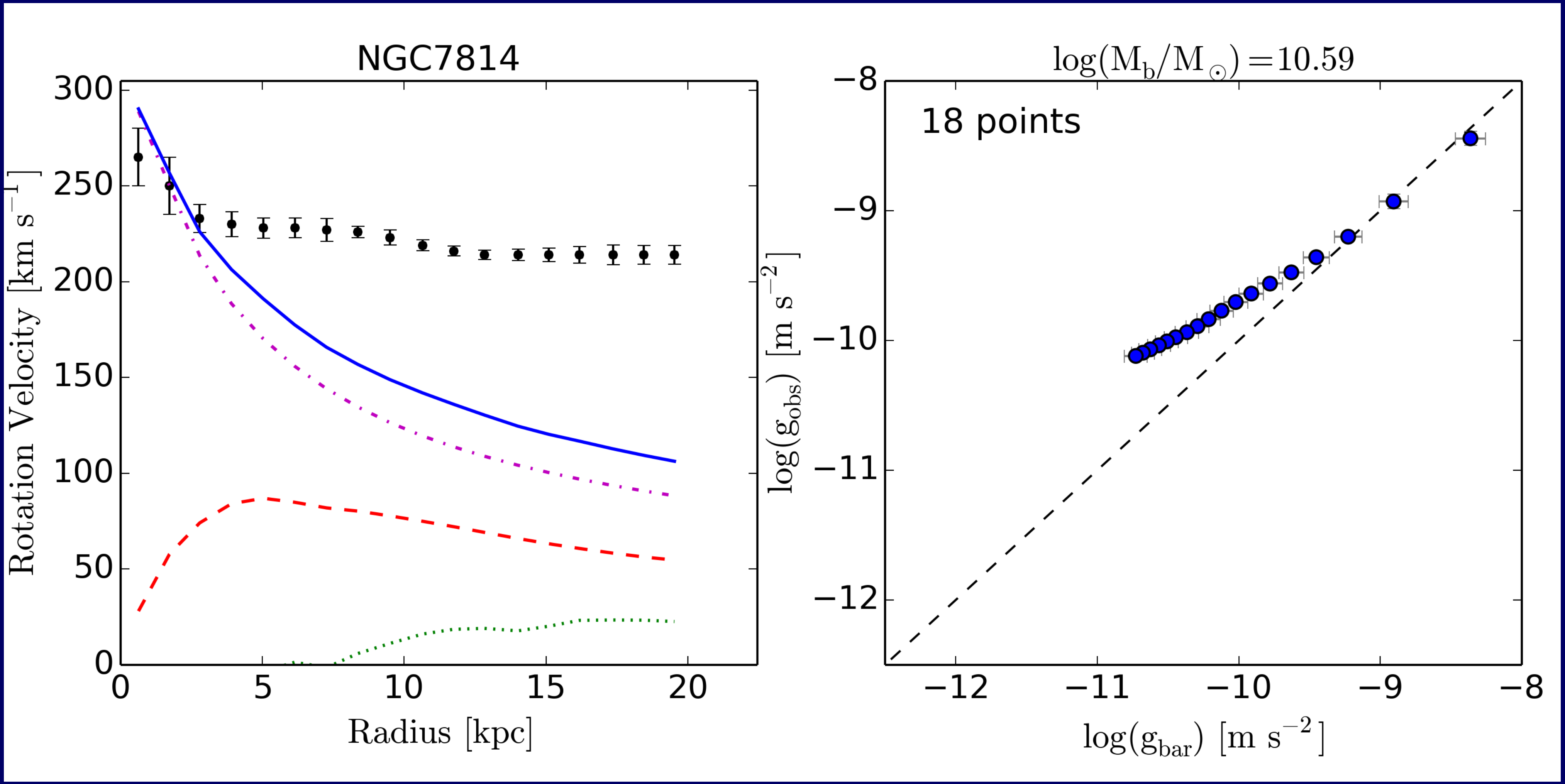
McGaugh, Lelli, Schombert (2016)

Building up the Radial Acceleration Relation

Large Diversity in Rotation Curves

Regularity in Acceleration Plane



Lelli, McGaugh, Schombert, Pawlowski 2017, ApJ

Video available at astroweb.cwru.edu/SPARC/

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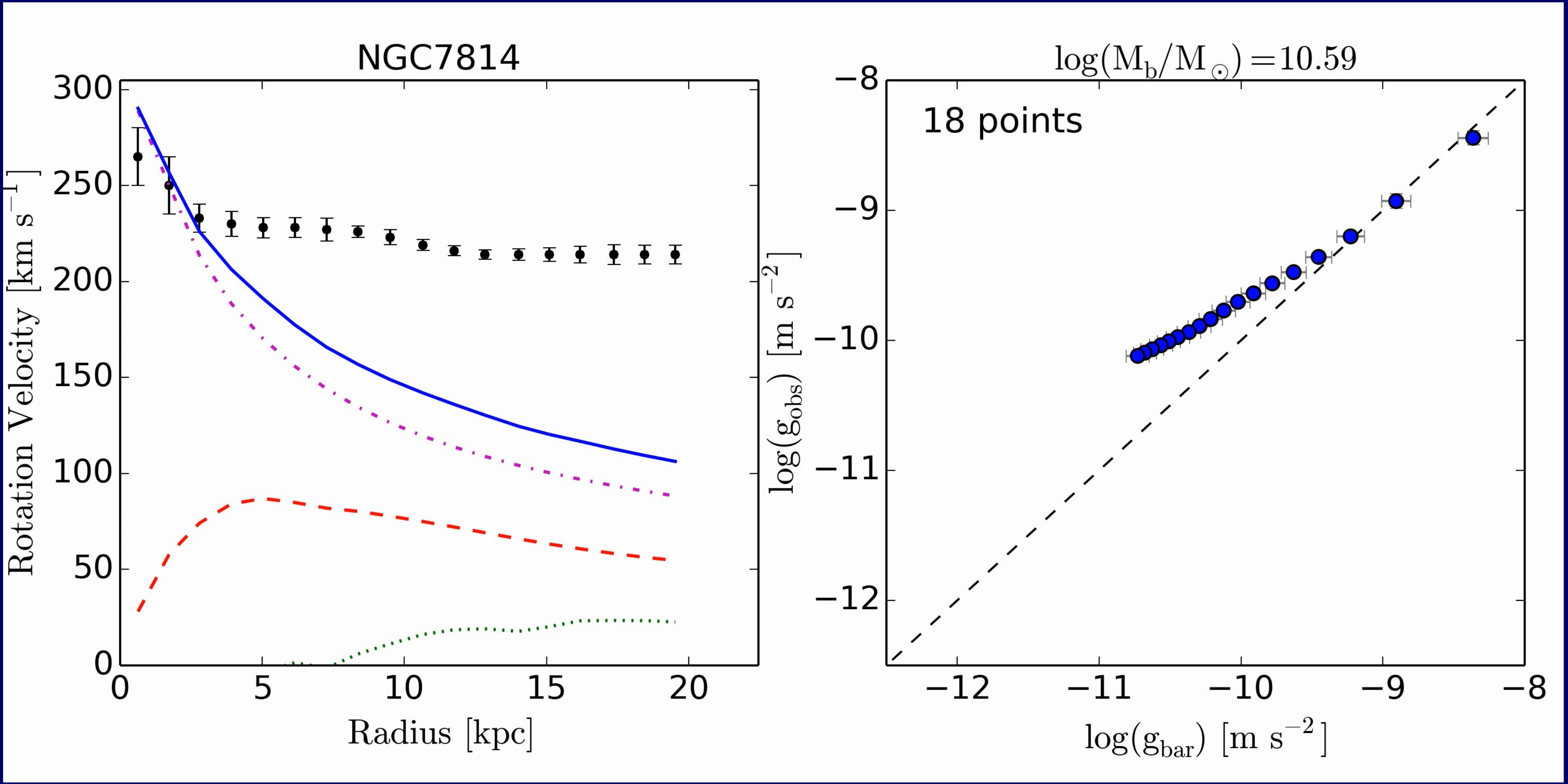

Lelli, McGaugh, Schombert, Pawlowski 2017, ApJ

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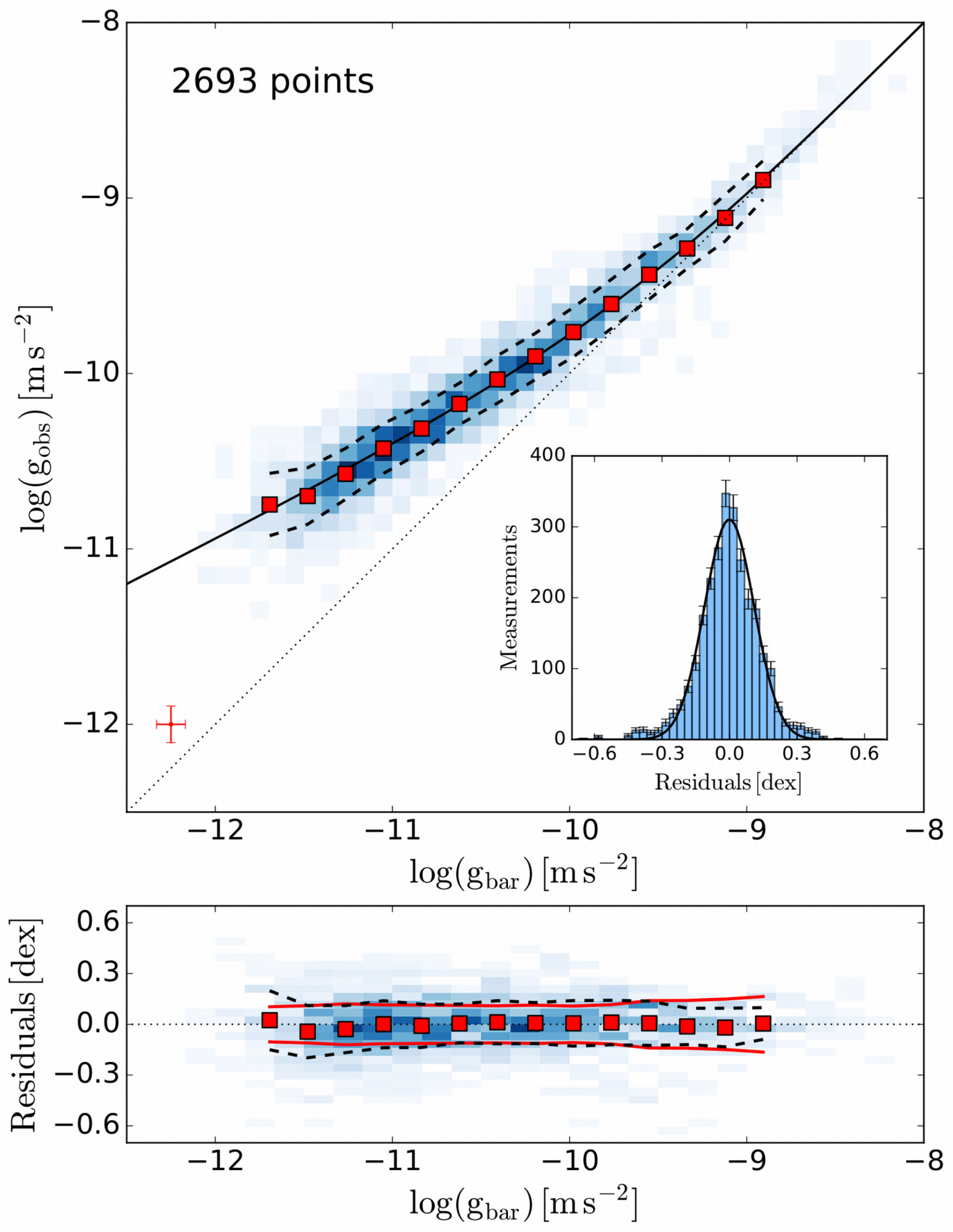
Is There Any Intrinsic Scatter?



Uncertainties drive scatter!

err(g_{bar}) → Υ_*, 3D geometry

err(g_{obs}) → Dist, Inc, V_{rot}

$$\sigma_{obs}^2 = \sigma_{err}^2 + \sigma_{int}^2$$

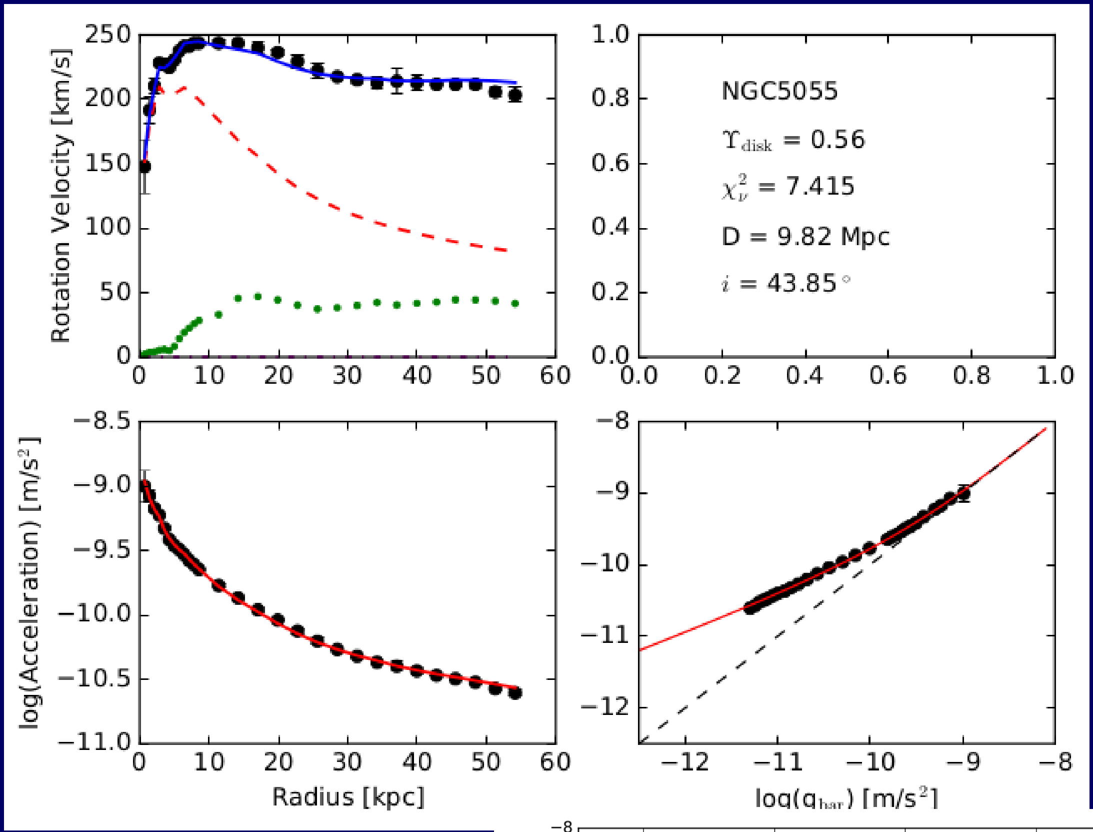
σ_{obs} → measured rms

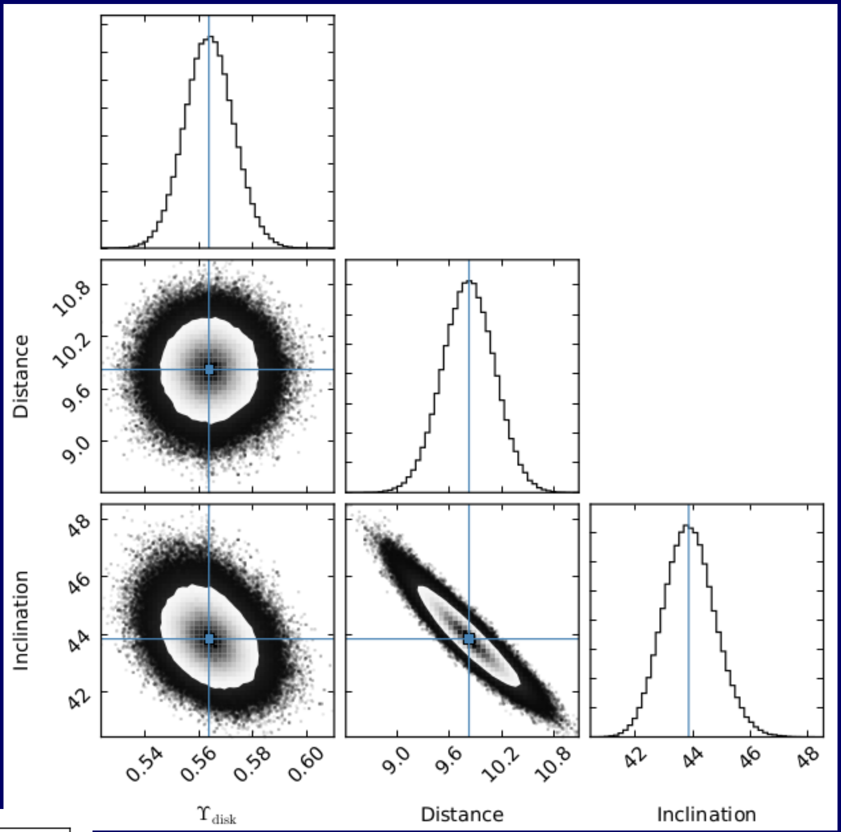
σ_{err} → error propagation

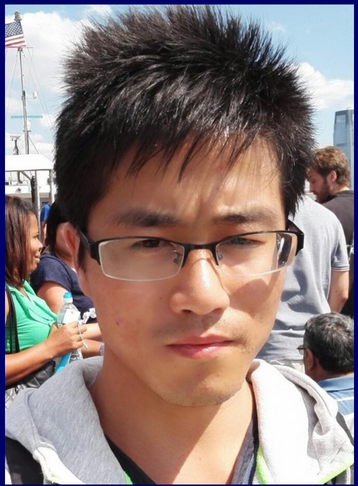
σ_{int} → consistent with zero!

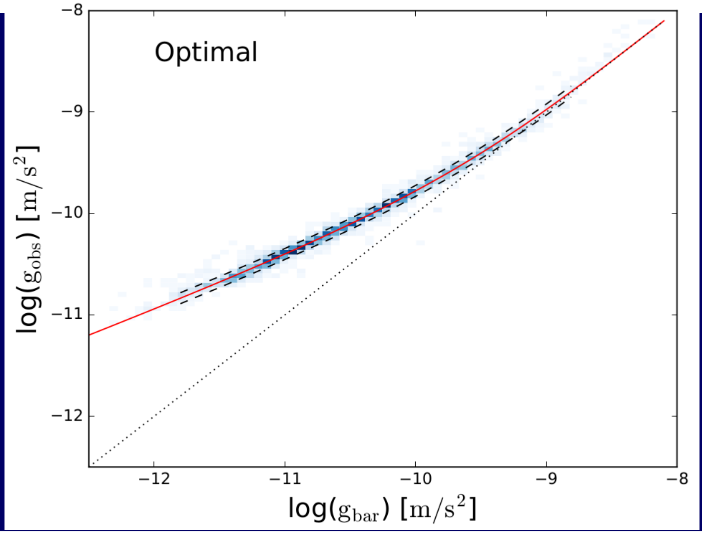
McGaugh+2016, PRL; Lelli+2017, ApJ

MCMC Fits to Individual Galaxies









Extremely tight relation!

σ_{obs} = 0.054 dex (~10%)

err(V_{rot}) ~ 10%

Pengfei Li et al. (submitted)

Three Laws of Galactic Rotation:

1. Global Law: $V_{flat} \propto M_{bar}$

2. Central Law: $\Sigma_{dyn}(0) \propto \Sigma_{bar}(0)$

3. Local Law: $g_{obs}(R) \propto g_{bar}(R)$

Only inputs are the Poisson Equation and the M_*/L.

Observed scatter is tiny. No residual correlations.

We can infer the DM distribution from g_{bar}!

From the observations: $$g_{DM} = g_{tot} - g_{bar} = F(g_{bar})$$

For a spherical DM halo: $$M_{DM}(R) = \frac{R^2}{G} F(g_{bar})$$

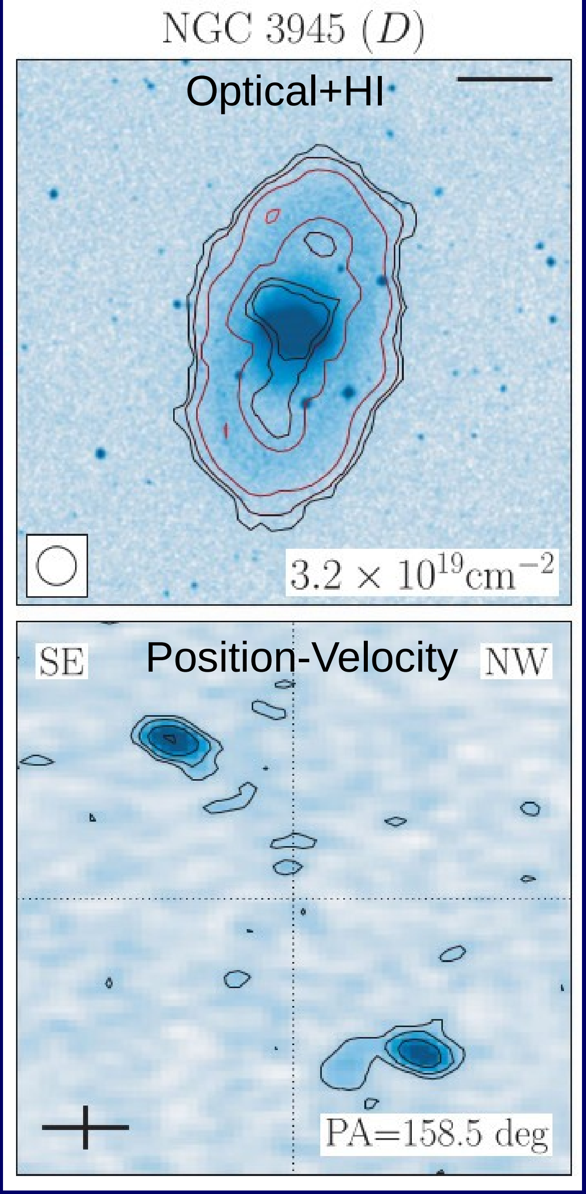
For our fiducial fitting F: $$M_{DM}(R) = \frac{R^2}{G} \frac{g_{bar}}{\exp(\sqrt{g_{bar}/g_0}) - 1}$$

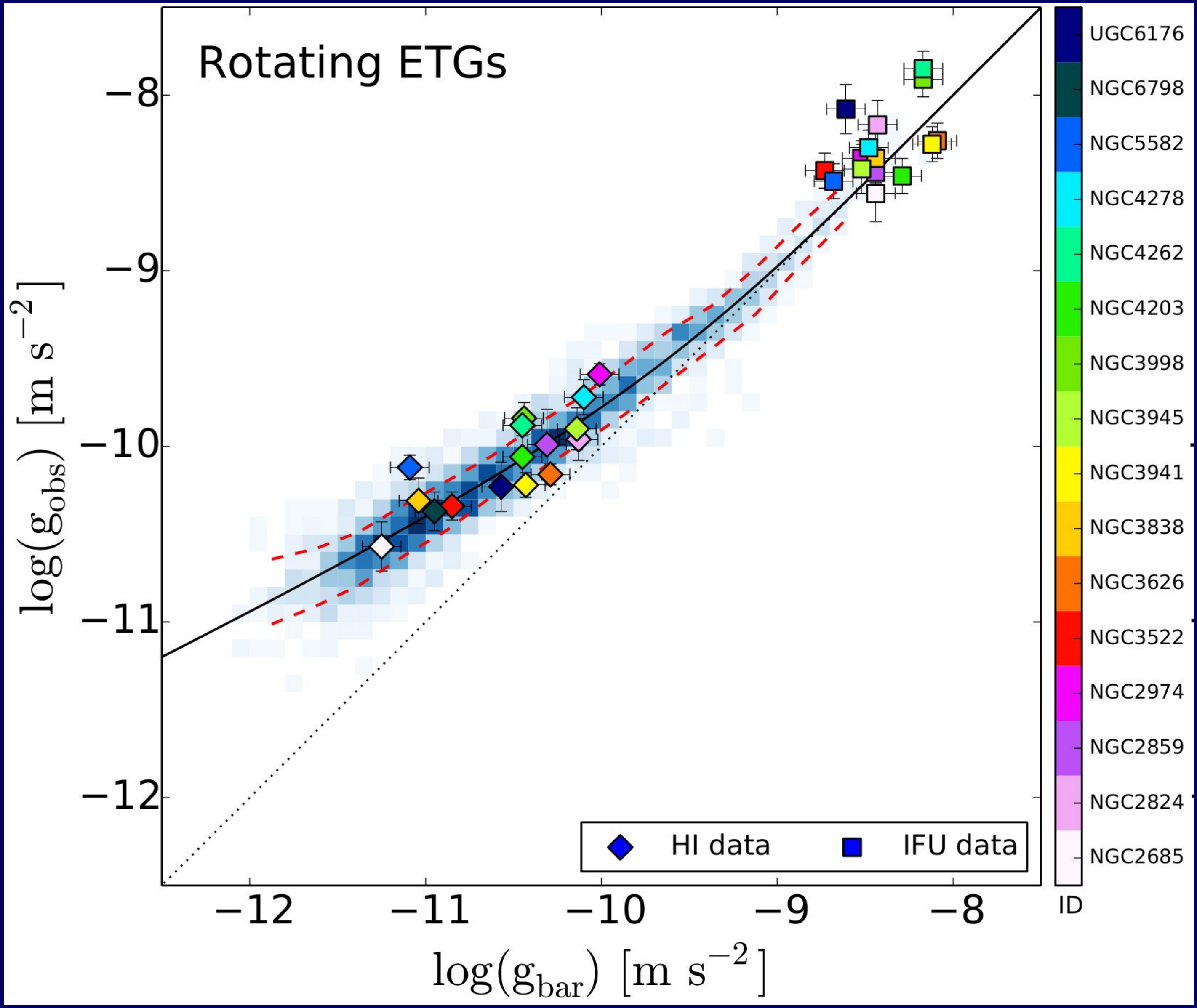
Purely empirical relations (accuracy ~30%).

3. Radial Acceleration Relation of Early-Type Galaxies

Lelli, McGaugh, Schombert, Pawlowski 2017, ApJ

16 Rotating ETGs with outer HI rings/disks

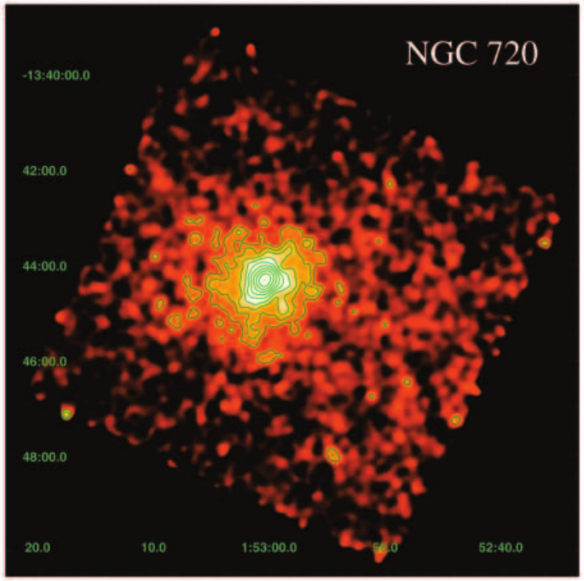


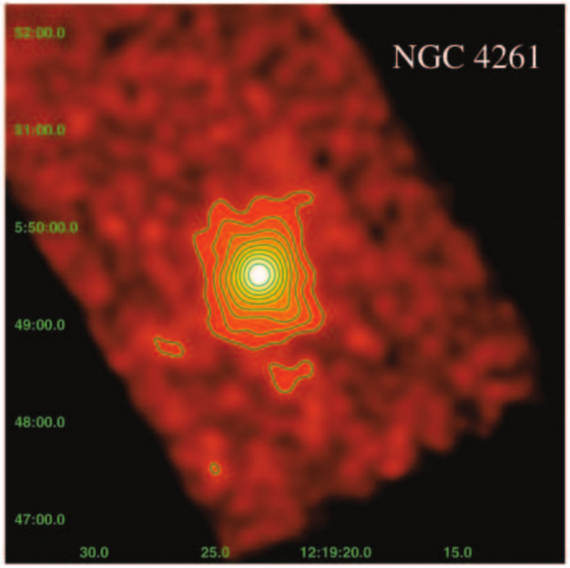


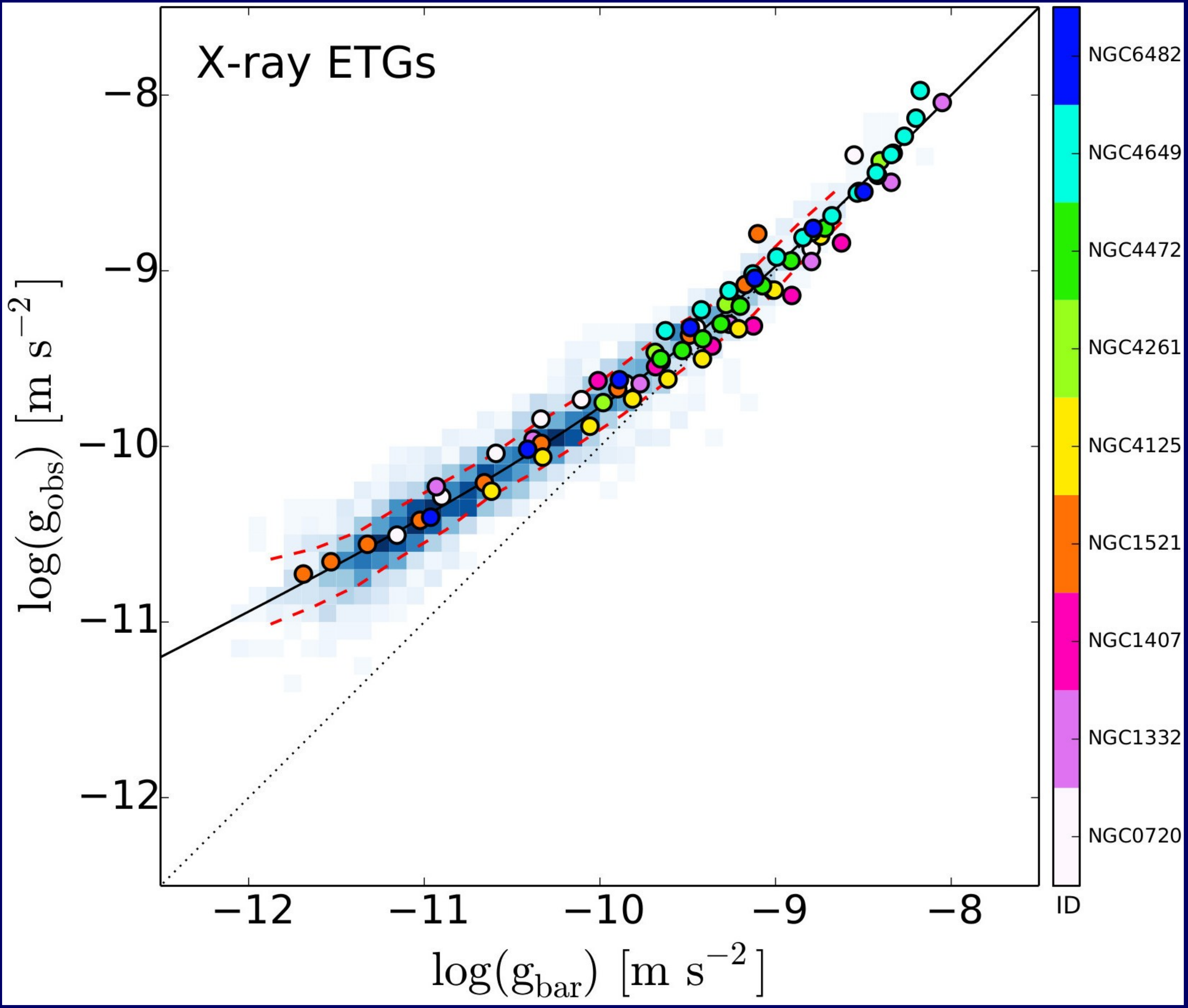
ATLAS[3D] project: Cappellari+2010; Serra+2012, 2016

Lelli+2017, ApJ

9 Non-Rotating ETGs with X-ray Halos



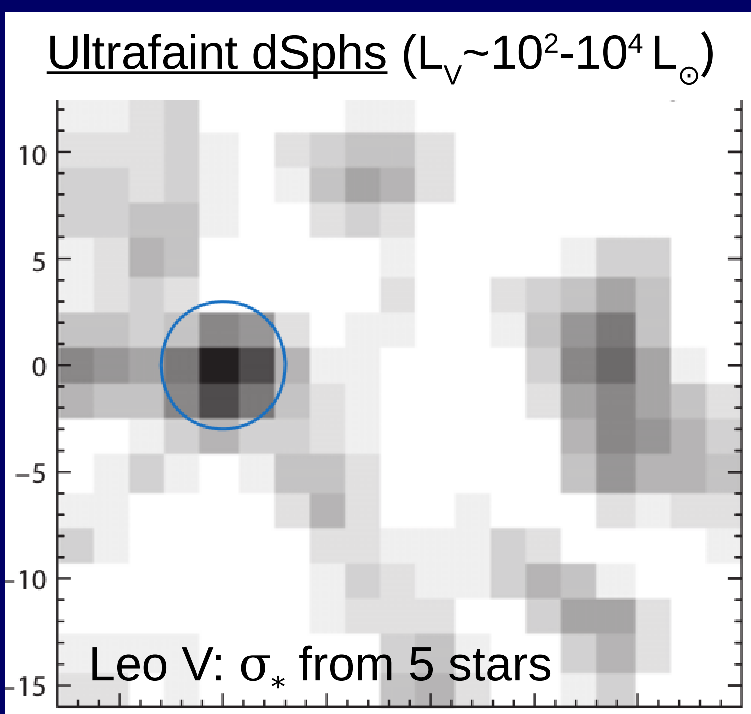


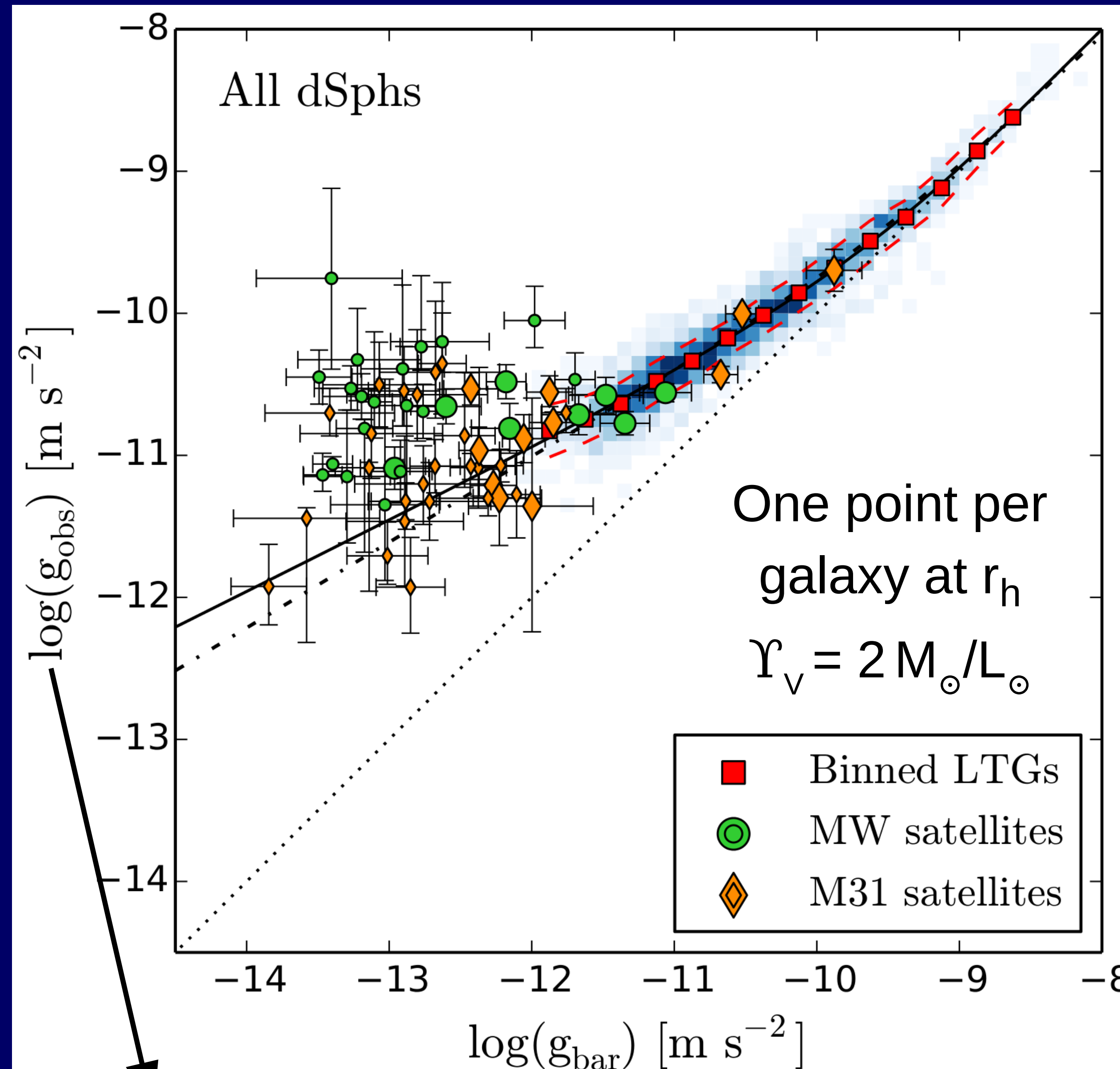


Humphrey+2006, 2008, 2009, 2011, 2012

Lelli+2017, ApJ

Dwarf Spheroidals in the Local Group

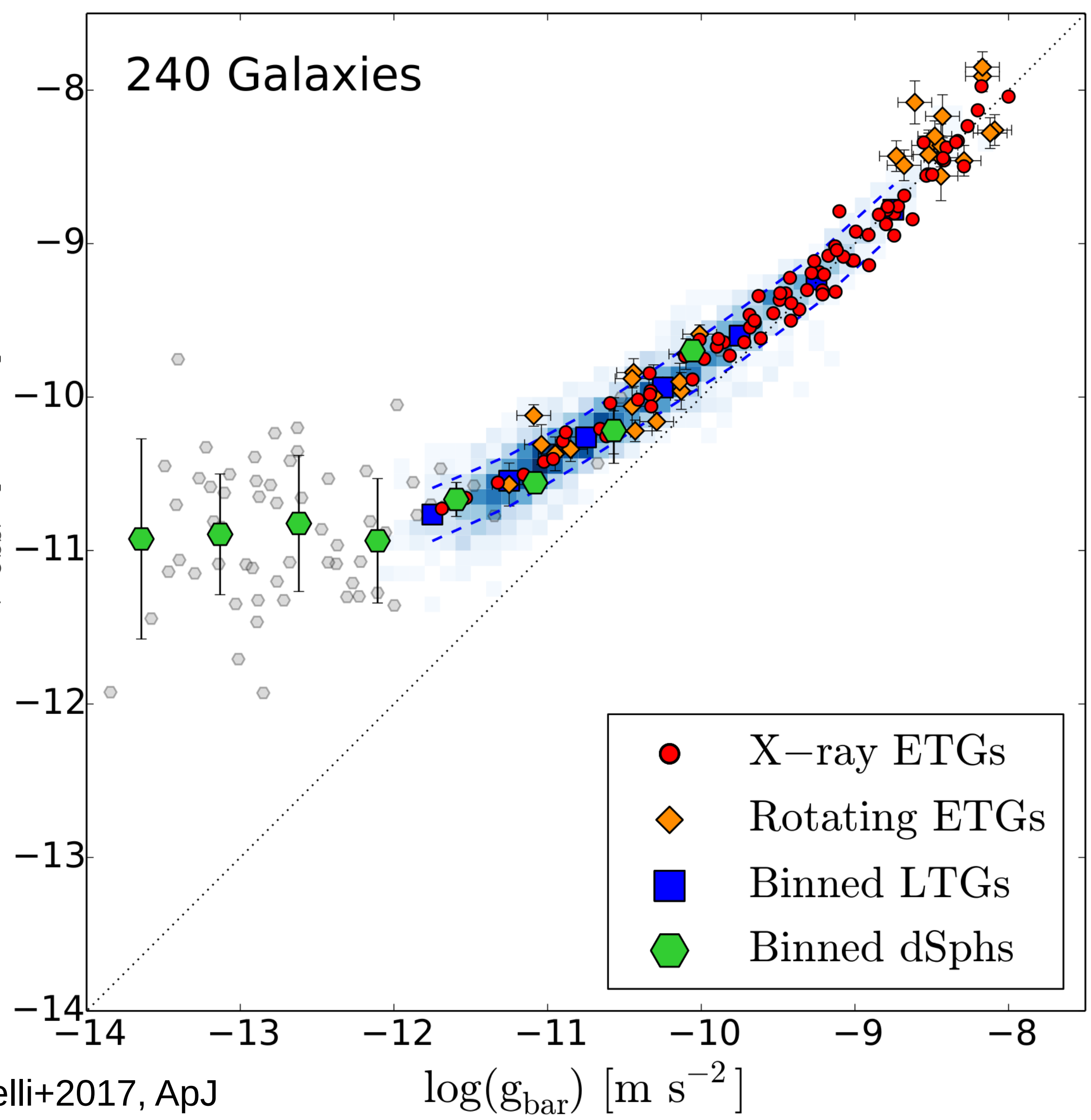




$g_{obs} = 3\sigma_*^2/r_h$

$g_{bar} = GM_{bar}/r_h^2$

One Law to Rule Them All!



Lelli+2017, ApJ

Possible Interpretations:

1. End product of galaxy formation in ΛCDM

2. New Dynamical Laws (Milgromian Dynamics)

3. New Physics in the Dark Sector / Dark Forces

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   Bad: Complex, stochastic process BUT galaxies are simple (σ_{int}<10%!).

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   Bad: CMB? Large-scale structure of the Universe? Galaxy clusters?

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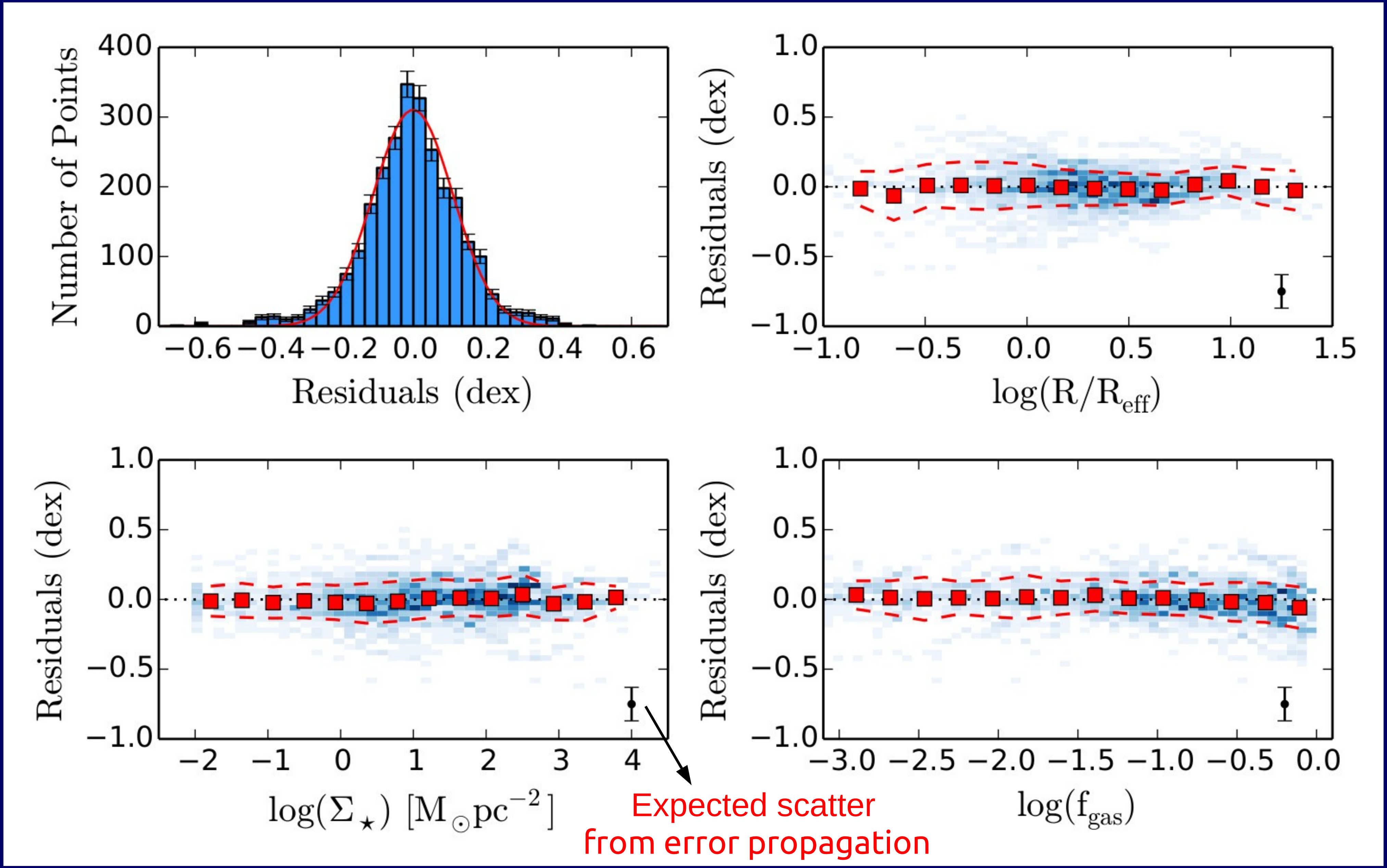
3. New Physics in the Dark Sector / Dark Forces

   Good: Hybrids ΛCDM + MOND (Dark Fluids: Zhao & Li 2010; Khoury 2015)

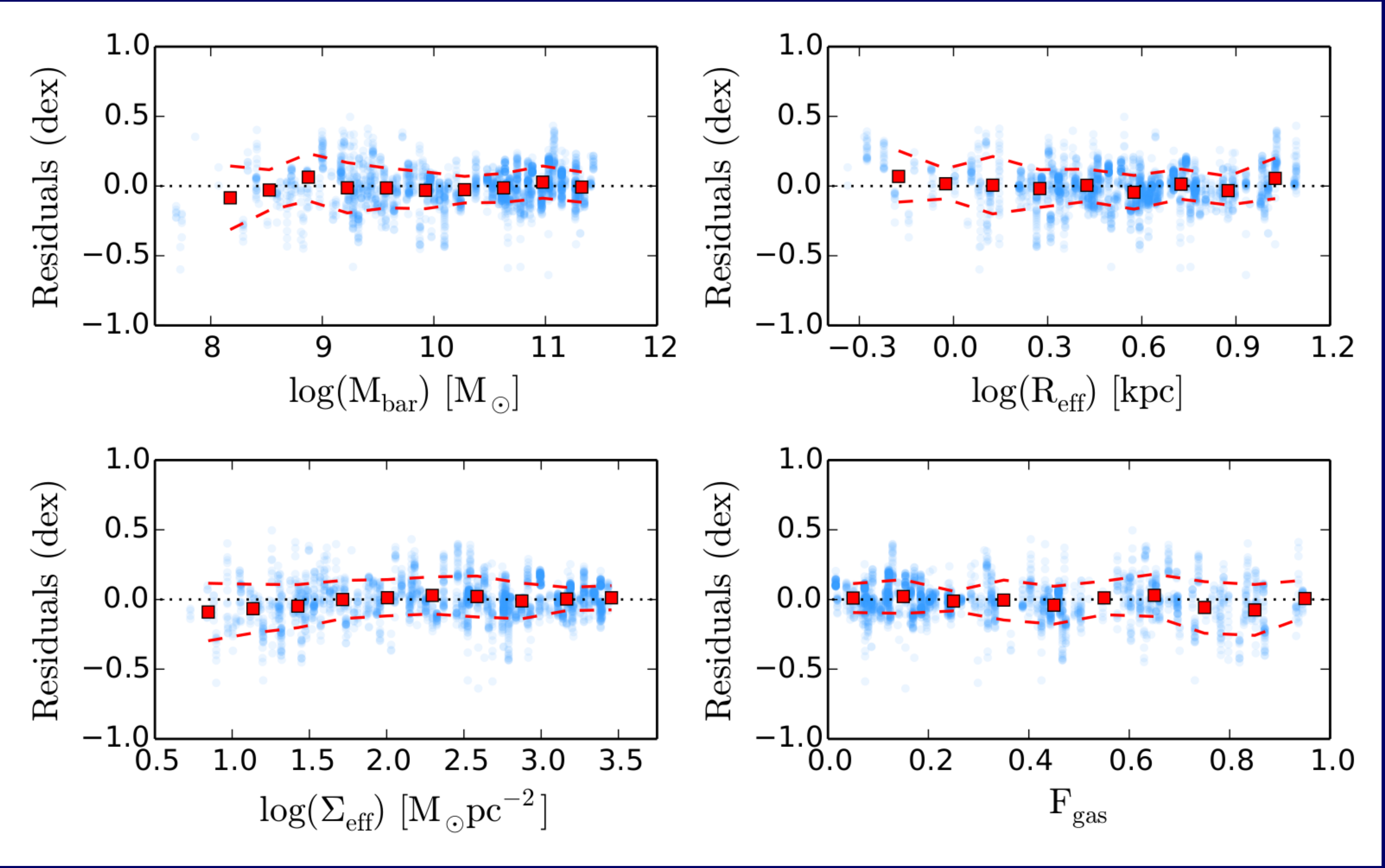
   Bad: 'Good' is good by construction. New predictions?

Additional Slides

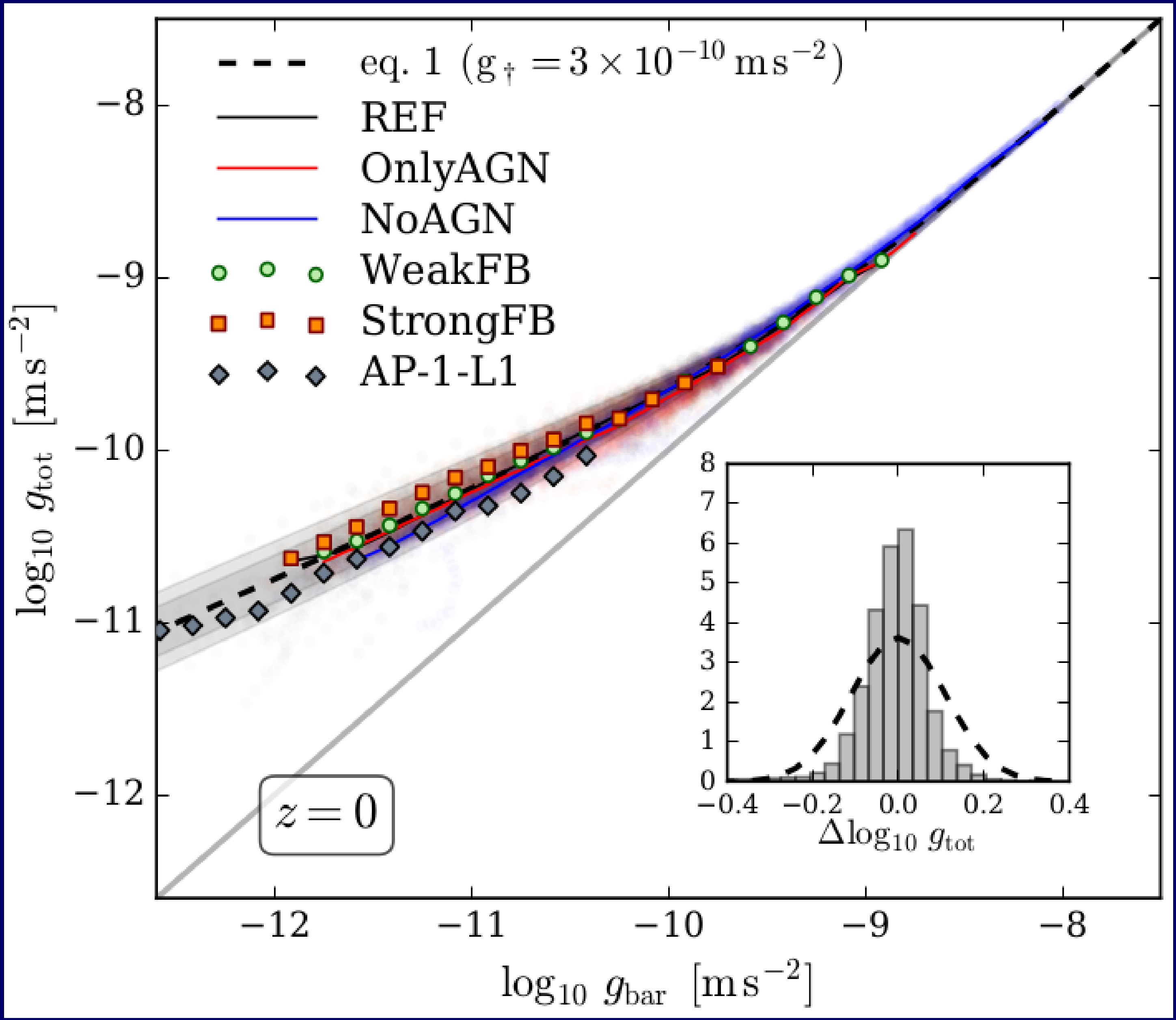
Residuals *vs* Local Galaxy Properties



Residuals *vs* Global Galaxy Properties



RAR from Hydrodynamical Simulations



A similar relation is found but the real problem is the TIGHTNESS!

$\sigma_{obs}^2 = \sigma_{int}^2 + \sigma_{err}^2$

Can't forget errors!

Analytic Models:

Di Cintio & Lelli 2016

Navarro+2016

Desmond 2017

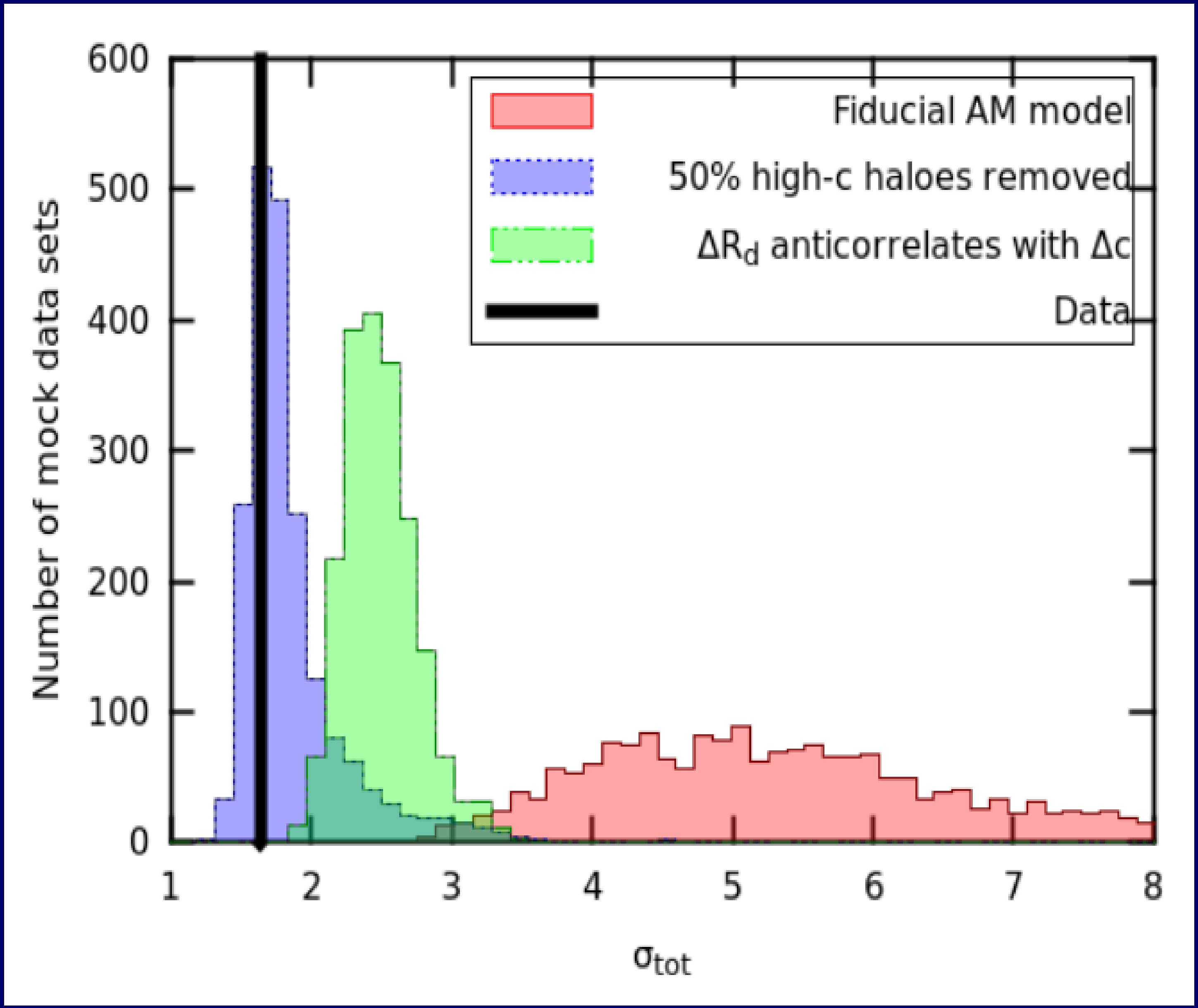
Numerical Sims:

Keller & Wadsley 2016

Ludlow+2017

Tenneti+2017

RAR Scatter from Semi-Empirical Models

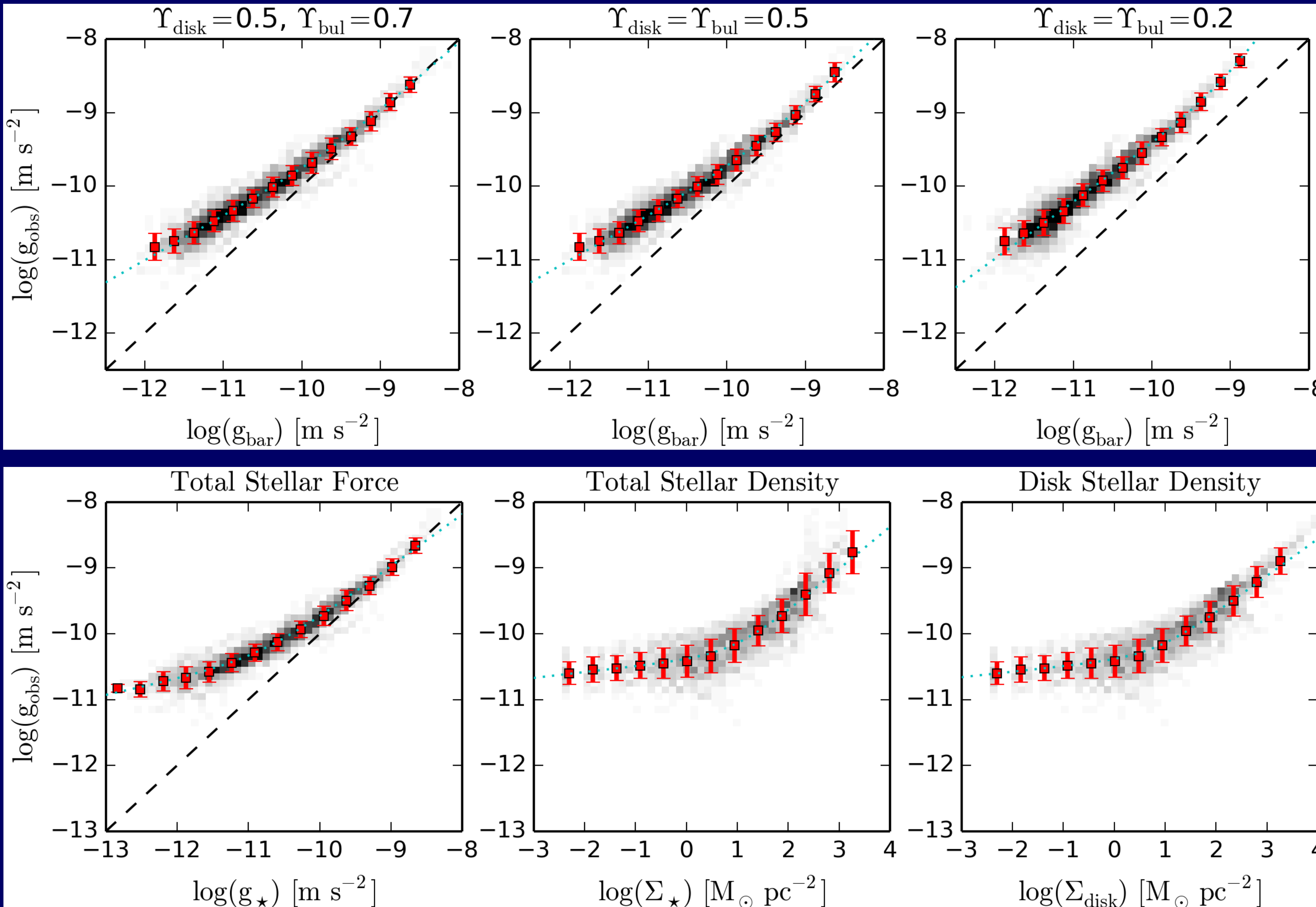


Each SPARC galaxy is associated to a DM halo by matching relative abundances (see also DiCintio & Lelli).

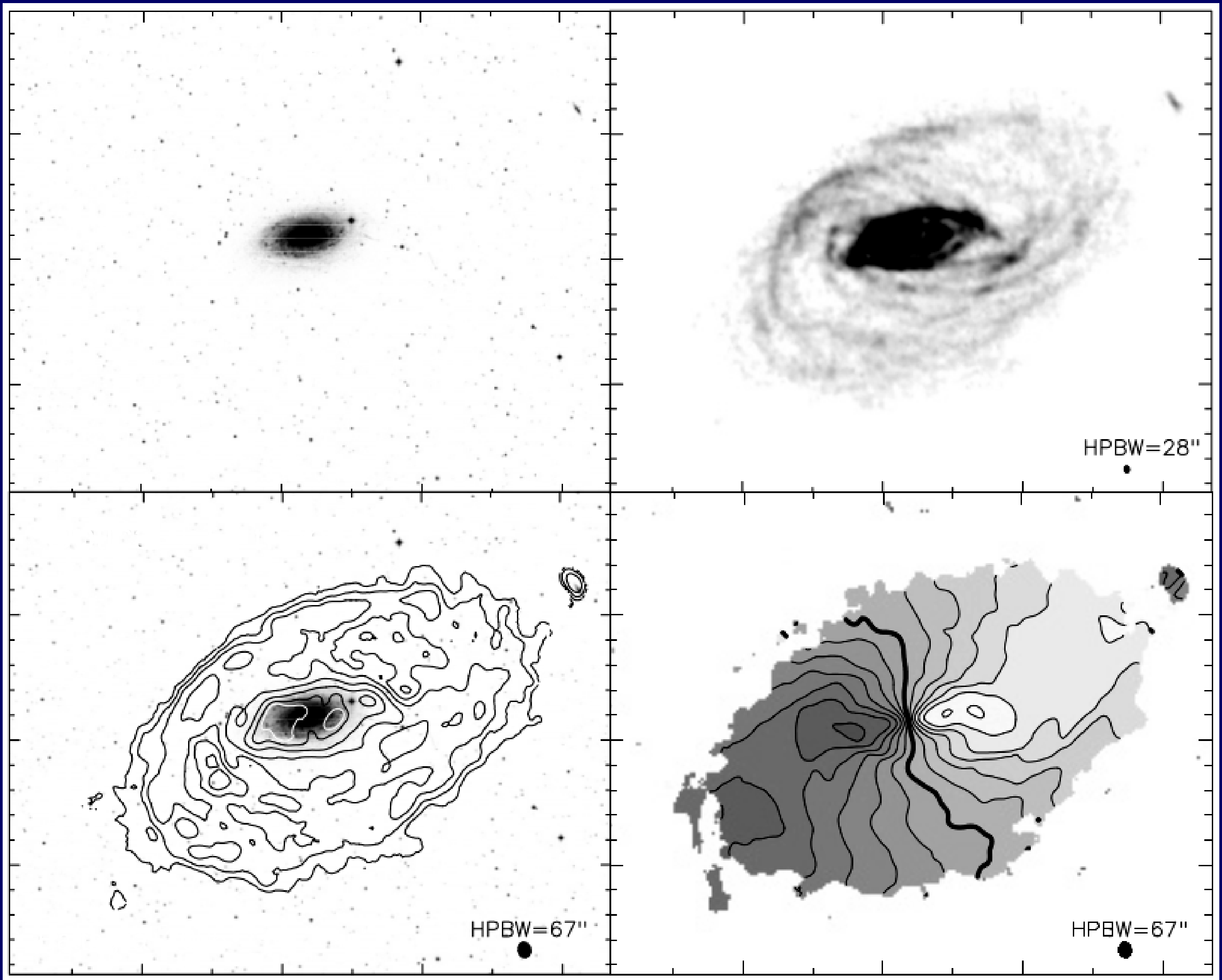
Multiple realizations taking into account sample variance and observational errors.

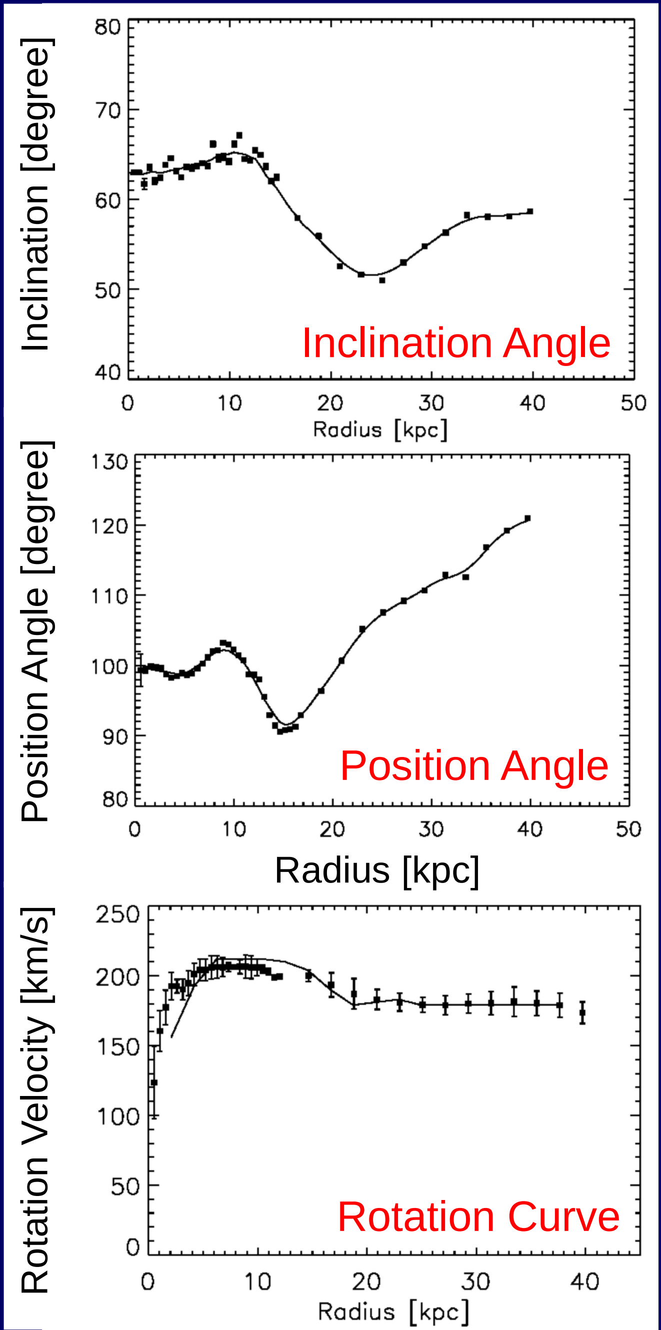
Fiducial model over-predicts the observed scatter!

Alternative versions of the RAR



HI observations: Rotation Curves

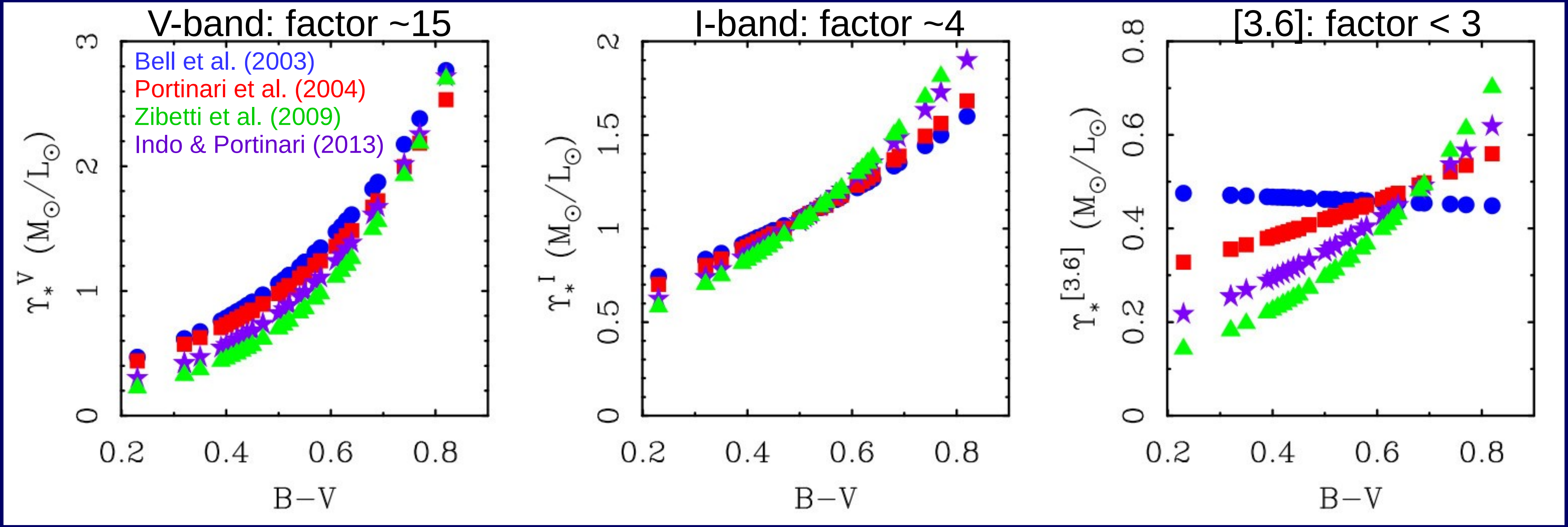




$$V_{l.o.s.} = V_{sys} + V_{rot} \sin(i) \cos(\theta)$$

$$\cos(\theta) = \mathrm{func}(x_0, y_0, PA)$$

Spitzer [3.6] Photometry: Stellar Mass

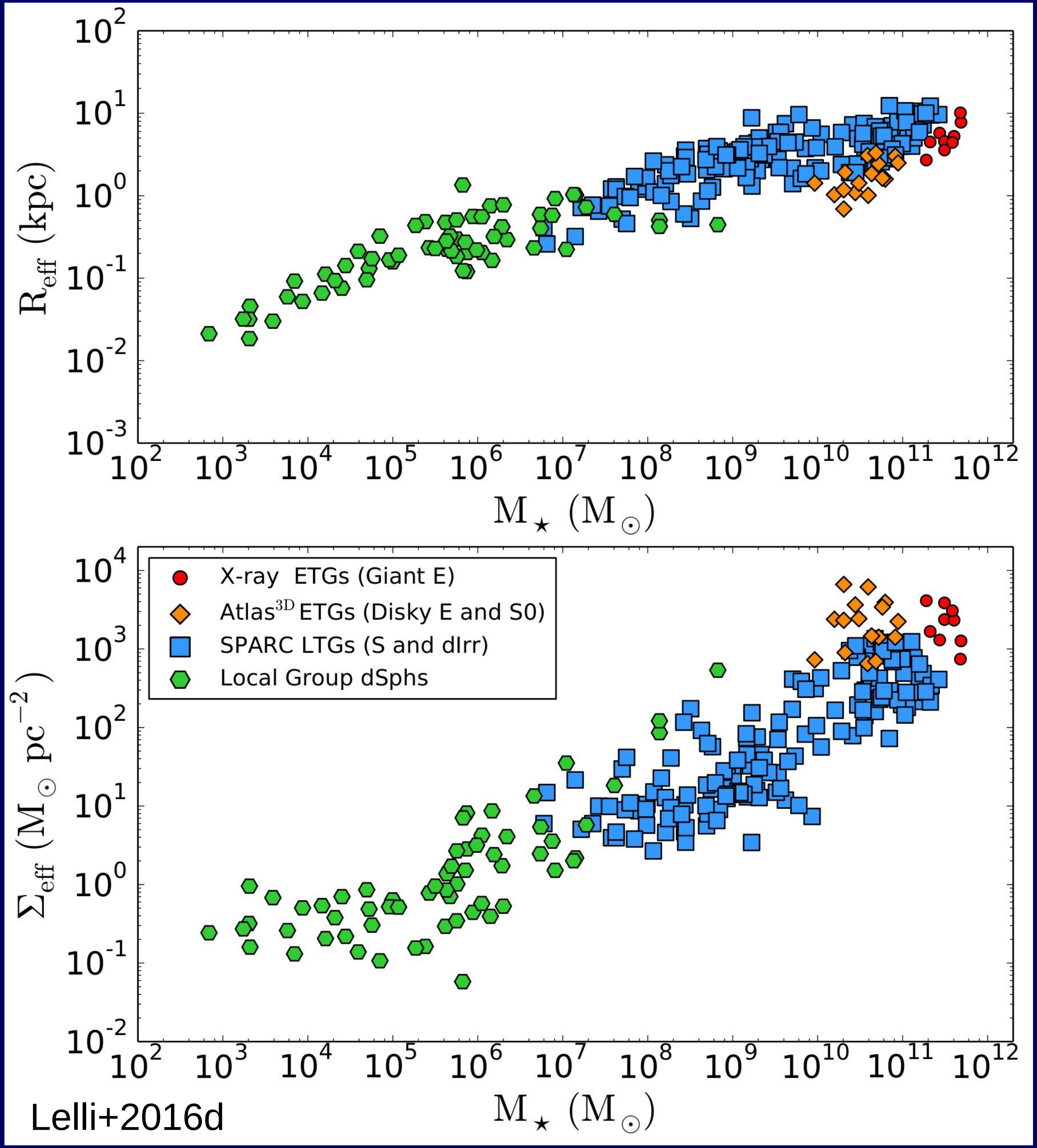


Υ_*-color relations from SPS models (McGaugh & Schombert 2014)

- Υ_* shows smaller variations at [3.6] than optical bands
- Details depend on SPS model and assumed IMF
- Most recent models: $\Upsilon_{[3.6]}$ is nearly constant for LTGs

(Meidt+2014; Schombert & McGaugh 2014; Norris+2016)

Dwarf Spheroidals (dSphs) in the Local Group



Satellites of MW and M31: extremely low masses, sizes, densities, and accelerations!

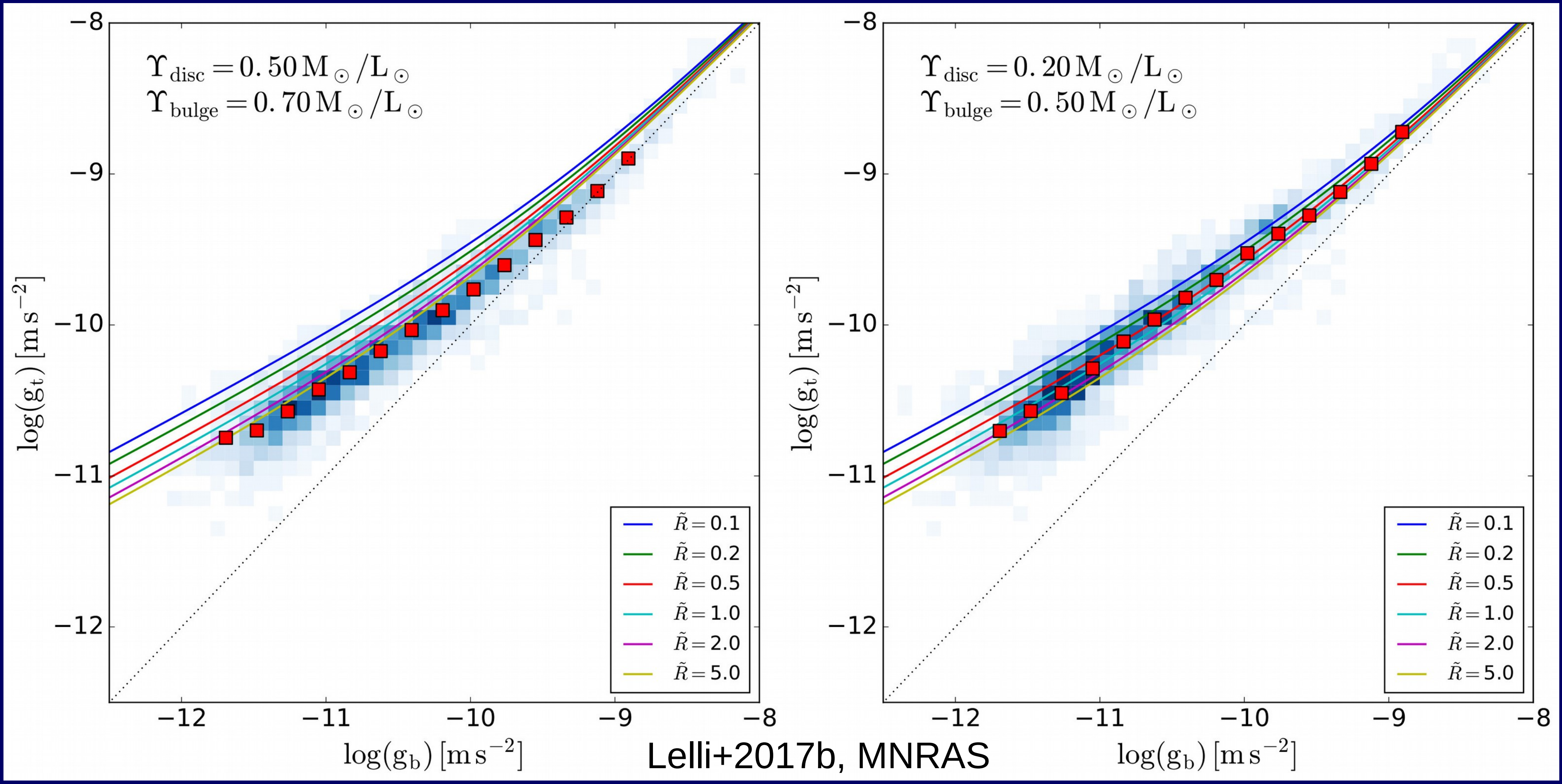
"Classical" dSphs discovered between the '40 and the '80.

→ well-studied properties

"Ultrafaint" dSphs discovered during the past ~10 years with SDSS, DES and other surveys

→ properties remain uncertain

RAR vs Verlinde's Emergent Gravity



EG implies: (1) low M/L on average
(2) some intrinsic scatter
(3) residual correlations with radius